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UNDERSTANDING RISK ASSESSMENTS FOR SOUR GAS PIPELINES

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by

CLAIRE MARY MCAULEY

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

MEDICAL SCIENCES – PUBLIC HEALTH SCIENCES

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University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Understanding Risk Assessments for Sour Gas Pipelines** submitted by **Claire Mary McAuley** in partial fulfillment of the requirements for the degree of **Masters of Science in Medical Sciences – Public Health Sciences.**

Dr. S. E. Hrudey

Dr. Jeremy Beach

Dr. Steve Craik

Date thesis approved by committee 20 August 2003

Abstract

A risk assessment of a hypothetical, sour gas (H_2S) pipeline located in Alberta was completed using data generated from a widely accepted dispersion model. The results were presented as three distinct endpoints on an exposure continuum; none was associated with catastrophic results.

The difference between risk to any individual in the general population, who experiences constant exposure, was calculated to be significantly higher than risk to a specific individual. The risk was compared to other involuntary risks (e.g. groundling fatality from airplane accidents) for magnitude and avoidance behaviour.

The importance of unknown and unknowable exposed populations was identified for pipeline ruptures and was compared with other situations where there is an unknown exposed population (West Nile virus, backcountry avalanches).

Pipeline ruptures occur and may have identifiable adverse public health outcomes; the investigation attempted to distill with clarity the risk assessment process and its communication problems.

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List of Abbreviations

AEGL	acute exposure guideline levels
AEUB	Alberta Energy and Utilities Board
C	concentration
CCPS	Centre for Chemical Process Safety
CEPA	Canadian Energy Pipeline Association
CPA	Canadian Petroleum Association
EEGL	emergency exposure guidance levels
EPA	U.S. Environmental Protection Agency
EPZ	emergency planning zone
ERCB	Energy Resources Conservation Board
ERPG	emergency response planning guidelines
ESD	emergency shut down
EUB	Energy and Utilities Board
FN	frequency-number affected
g/mol	grams per mole
H_2S	hydrogen sulphide
ID	inner diameter
IDLH	immediate danger to life and health
L	toxic load
LBV	line break valve
LC_{10}	lethal concentration to 10% of the population
LC_{50}	lethal concentration to 50% of the population

LOAEL	lowest observable adverse effects level
m/s	metres per second
mg/m^3	milligram per cubic metre
MIACC	Major Industrial Accident Coordinating Committee
n	toxic load exponent
NIOSH	National Institute of Occupational Health and Safety
NOAEL	no observable adverse effects level
NPV	negative predictive value
OME	Ontario Ministry of Environment
P(exp)	probability of exposure
P(x)	probability of variable x
PBPK	physiologically-based pharmacokinetic
PD	probability of lethality
PD1%	probability of lethality of 1%
PD100%	probability of lethality of 100%
ppb	parts per billion
ppm	parts per million
PPV	positive predictive value
RfD	reference dose
ROW	right of way
RR	relative risk
SCADA	supervisory control and data acquisition
t	time

TDI	tolerable daily intake
TSR	Triple Shifted Rijnmnond
UF	uncertainty factor
μg/m^3	microgram per cubic metre

1.0 Introduction

The objective of this project was to complete a risk assessment for a hypothetical and generic sour gas (hydrogen sulphide, H_2S) pipeline, and then to use the assessment generated to identify key areas of concern, understanding and misunderstanding. These issues can, at the time of project development, create a conflict between industry and the community that will divert energy away from seeking constructive solutions because the parties will not share a common understanding of the problems.

The complexities of the risk issues, associated with siting of sour gas facilities, combined with a variety of gaps in our knowledge provide considerable scope for creating misunderstanding throughout the risk assessment process. There is no absolute or ideal way in which to perform and present a risk assessment under the circumstances; however, by working through the process and then questioning the reasoning and logic behind the method, it may be possible to reveal sources of misunderstanding.

A decision was made to generate tangible numbers by conducting a hypothetical risk assessment based on realistic conditions rather than attempting to critique an existing risk assessment. If an existing risk assessment had been used, a full appreciation of the sources of the risk estimates would have been more difficult to achieve. The approach taken in this thesis involved the utilization of a set of risk estimates generated through the completion of a risk assessment, in order to illustrate those issues that may be primary sources of confusion and misinterpretation.

In order to provide greater reality for the project, the pipeline was conceived as running through an area of the Province of Alberta near the author's residence. This choice facilitated the definition of population density, topography, vegetative cover, traffic and meteorology by providing a tangible environmental setting for selecting all of the key parameters. Once the assessment was completed, it was used to generate questions that may arise because of a divergence between technical knowledge and public views. The questions posed were those that may be expected from a community and through re-analyzing the risk assessment in this manner the details were re-evaluated to determine what they really meant, and what underlying assumptions had been made that may not be entirely obvious to the public.

Areas of ~~public~~ concern as identified in the Public Safety and Sour Gas workshops were addressed (Provincial Advisory Committee on Public Safety and Sour Gas, 2000) including: dispersion of sour gas, low-lying areas and their effect on sour gas concentration, dependence on wind direction and meteorology, odour threshold, plume structure, how safe is safe?, acute toxicity and toxic load. Chronic toxicity (the long term effects of repeated or prolonged low dose exposures) was not addressed because: 1) chronic toxicity is not a probable result of a pipeline failure; and 2) Alberta Health and Wellness is pursuing ongoing study of this subject (AEUB, 2002).

A risk assessment was completed for a sour gas pipeline with two plausible gas compositions, each with a different H_2S concentration representative, of gas which is routinely shipped in Alberta. The data used in the risk assessment are presented in Chapter 2. The hazard identification and assessment for the generic pipeline are presented in Chapter 3. The toxicity assessment and a general discussion of probit analysis and the Triple Shifted Rijnmond equation are presented in Chapter 4.

In Chapter 5 the results from the dispersion models are presented in a format similar to that proposed in the Draft Hazard and Risk Analysis Protocol (AEUB, 2002). The exposure assessment is also presented in Chapter 5 with a discussion of the different endpoints on the continuum of exposure.

The risk assessment for the generic pipeline and the plausible gas compositions is presented in Chapter 6. A computer spreadsheet was developed to simulate the differing levels of individual risk that may be encountered in a plume of sour gas at distances downwind of the release. Individual and societal risks were identified and compared for both gas concentrations downwind of a release. Frequency - Number affected (FN) curves were discussed and the specific curves for the situations assessed were included.

In Chapter 7 uncertainty and variability are explained as applied to a pipeline rupture analysis and the use of frequency statistics is discussed as a basis for probability judgements. The risk variables are identified and their probability density functions discussed. A Monte Carlo and sensitivity analysis of the data was performed. This analysis identified those variables in the exposure equation that most strongly determine the annual individual risk estimate. The sensitivity analysis is useful in the risk management stage of the problem, in the identification of all appropriate and available mitigative measures that may reduce the risk. The uncertainty about the quantitative dose-response toxicology of hydrogen sulfide is the principal contributor to uncertainty.

In Chapter 8 the risk levels are described and the shortfalls associated with the assumptions are detailed. The aspect of a continuous receptor and the difference between risk to any individual (assuming a constant receptor) and risk to a specific individual is identified. Parallels are drawn between the risk profile for risk of fatality within a contaminant plume and the risk profile for a groundling (person on the ground) fatality from an airplane accident.

In Chapter 9 the difference between risk to any individual (assuming a constant receptor) and risk to a specific individual is further developed. Similar risk analogies for other known risk scenarios where there is a defined receptor population but no specific receptor are identified and discussed.

Chapter 10 addresses the issue of the significance and acceptability of risks and Chapter 11 identifies and discusses ethical principles for risk management and their application to environmental health risk assessment.

Landowners, who may be affected by oil and gas development, commonly react to the prospect of danger being externally imposed. The danger associated with a rupture of a sour gas pipeline and the lack of control over the situation associated with the existence of a facility on their land, cause an understandable emotive response. The risk assessments are complex, difficult to understand and apparently uncertain; overall not very reassuring to those who are already unhappy with the prospects of facing external imposition of danger.

While all models are approximations and mathematical representations of potential situations and the technical inputs required are extensive, new forensic evaluations using actual meteorology have been completed to validate the plume dispersion models. Forensic modelling is modelling which occurs after an actual release. The actual meteorology and wind conditions are used in combination with real time occurrences and actual geographic and population conditions in the dispersion model in order to ascertain the path of the release, the areal extent of the plume and to identify the individuals affected by both contaminant and odour. These forensic runs show near replication of model results. This understanding of the plume dispersion characteristics and the potential "sphere of influence" of an H_2S release may facilitate greater public understanding of the risks posed by releases from sour gas facilities. The issue of forensic modelling and the strengths of the dispersion model are identified.

The development of more sour gas projects in closer proximity to established population centres has understandably generated increasing public concern regarding the development of sour gas facilities in close proximity to existing dwellings. The Alberta Energy and Utilities Board (herein referred to as the EUB) setback distances are currently under review. The prevalence of anecdotal reports regarding chronic effects of H_2S exposure, combined with the publicity surrounding the eco-terrorism activities of Weibo Ludwig, have created a climate that does not foster public understanding of the effects of sour gas development and the mitigative measures required and undertaken for such developments.

2.0 *Project Information and Assumptions*

Pipeline ruptures and leaks have the potential to cause significant adverse public health effects. Increasing numbers of sour gas developments are being proposed in close proximity to existing communities, while increasing numbers of people are opting for rural and acreage living bringing residential development closer to existing and new sour gas developments. These trends, combined with the depletion of conventional sweet oil and gas reserves and an increasing number of sour fields being developed, accentuate the need for the risks and misconceptions regarding sour oil and gas development to be identified and addressed.

This risk assessment has been performed on a hypothetical sour gas pipeline located in central Alberta. The pipeline does not exist, rather it was "created" in order to complete a risk assessment utilizing screening level conditions and existing data from pipeline break simulations and to generate questions about risk, uncertainty and the underlying need for improved risk communication.

RWDI West Inc., a consulting engineering company located in Calgary, AB, was retained by the Alberta Energy and Utilities Board (EUB) in November 2000, to evaluate the emergency planning zone criteria applied in Alberta. The numerical data from the dispersion modelling performed by RWDI West Inc. for their contract with the EUB formed the basis of the risk assessment completed on the generic pipeline. The modelling data generated by RWDI are included as Tables 5.2, 5.3, 5.4, 5.5, 5.6, and 5.7 and categorize the distances to various endpoints under different meteorological conditions. The data interpretation, exposure assessment, risk analysis and risk interpretation presented in this thesis were facilitated by assistance from RWDI West Inc. but they represent my original work and were not part of the RWDI West Inc. contract.

Representative gas analyses were used in the simulation of pipeline ruptures. Dispersion models of two concentration scenarios were utilized to calculate and compare the plume spreads generated by the ruptures. All of the raw data utilized in this risk analysis were generated by the SLAB dispersion model, with the input conditions being modelled through a transient release model with adiabatic gas expansion upon release. The downwind concentrations of the plume were the input parameters into the consequence model that allowed for the generation of the exposure distances. While SLAB is a publicly available dispersion model, the necessary input and output batch files required to model gas expansion and produce meaningful consequence data are proprietary property of RWDI West Inc.(Calgary).

Historically, two dispersion models were used in Alberta for sour gas release modelling, SLAB and GASCON2; a recent decision of the EUB however now requires the use of SLAB (AEUB, 2002). In order to enable public use of SLAB, batch programs for manipulation of input and output files will become publicly available. Based on the recent EUB decision there were no data from GASCON2 simulations utilized in this risk assessment.

2.1 Engineering Information

The hypothetical pipeline is an "8-inch" schedule 40 pipe with an outer diameter of 219.1mm and an inner diameter of 202.7mm. The wall thickness is 8.18mm and the material of construction is carbon steel; the line is internally bare and is externally coated with yellow jacket. The line is buried 1 meter below ground and has emergency shutdown valves (ESDs) on either end of the segment lengths as described herein. The process operating pressure is 10000 kPa and the temperature of the process gas is 5 °C. It is proposed that the pipeline has a north/south orientation. The operating conditions for the pipeline are presented as Table 2.1. These pipeline conditions are realistic for sour gas pipelines in rural Alberta.

Table 2.1 - Pipeline Operating Conditions

Parameter	Value
Outside diameter	219.1mm
Inside diameter	202.7mm
Wall thickness	8.18mm
Operating pressure	10000kPa
Operating temperature	5°C
Burial depth	1.0m

2.2 Site Characteristics

It is assumed that the hypothetical pipeline is a below-ground line that runs through rural central Alberta in an area southwest of the City of Edmonton, a mixed area of pasture land and bush with gentle surface topography. The shallow groundwater contours are assumed to follow the surface contours. The road structure is one of range roads running north-south every mile and township roads running east-west every two miles, providing a grid like pattern typical to much of the centre of the Province. The pipeline is assumed to pass under roads and creeks but not under significant water bodies (lakes or rivers). For the purposes of the model the topography and surface vegetation, as defined by the surface roughness characteristic, are gently rolling and lightly treed, respectively. A densely forested area would have caused potential surface entrainment of contaminant causing a smaller concentrated zone of influence for the gas. An assumption of lightly treed provides a scenario resulting in a greater areal extent of the contaminant allowing for greater dilution and geographic dispersion. The resulting greater areal extent corresponds to a greater number of people being potentially affected by a release. With an assumption of a heavily treed location, the contaminant has a potential to affect fewer people more severely (than a release over a greater geographic extent) but only in close proximity to the actual release.

The land use in the vicinity of the pipeline is assumed to be farmland with areas of undeveloped bush. Recreation areas are also assumed in the vicinity (campgrounds, community halls) where the immediate population of the area would increase for short periods of time.

2.3 Meteorological Data

There are two weather-monitoring stations in the study area southwest of Edmonton; one at the Edmonton International Airport operated by Environment Canada and one in the area of Tomahawk (located east of Drayton Valley) operated by the West Central Airshed Society. Owing to the completeness of the data set, the data and frequencies from the International Airport are used in the determination of the predominant wind direction. Figure 2.1 is a windrose diagram, showing a combination of wind direction and wind speed frequency, from the weather station.

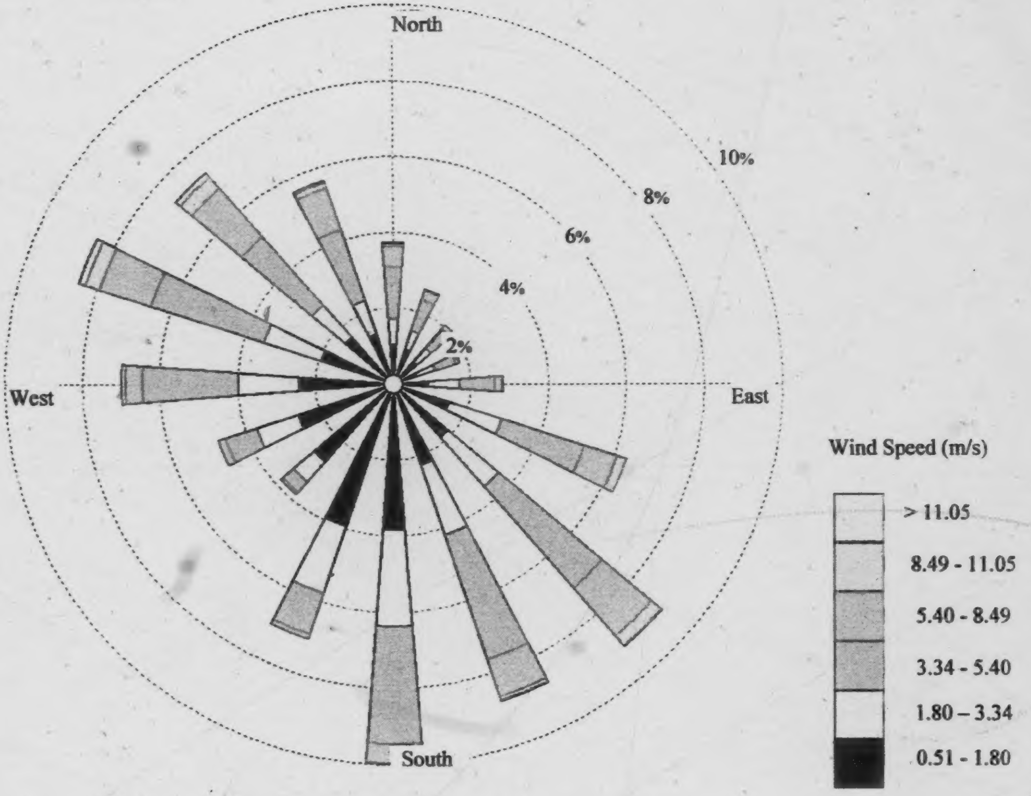


Figure 2.1 - Wind Rose Diagram Edmonton International Airport (Environment Canada, 1996)

Weather conditions during a pipeline release affect the size and location of the hazard area. Wind direction determines the direction of plume dispersal, and atmospheric stability and wind speed determine the dilution and mixing capabilities of the atmosphere and therefore the extent of the hazard. Pasquill and Gifford (Pasquill, 1960) defined atmospheric turbulence based on six stability classes (A-F). Classes A, B, and C refer to the unstable conditions encountered during daylight hours caused by the thermal turbulence associated with the ground heating of low lying air becoming less dense and rising creating vertical atmospheric motion. Class D is a condition of neutral stability where, under cloudy skies or during periods of high winds, mechanical turbulence (wind) dominates over thermal turbulence. Classes E and F refer to the stable conditions that occur under clear night skies when the air in contact with the ground will cool and become denser than the air above it. This increased density prevents vertical motion and creates a stable atmosphere. The Pasquill-Gifford classes are combined with wind speeds to generate an alphanumeric nomenclature describing the stability class and the wind speed in meters/second. (i.e. B2 is an unstable environment of level B where thermal turbulence dominates and there is a wind speed of 2 meters/second.) In the risk assessment, in order to represent more cautious conditions, weather categories D2, D5, D10, E3 and F2 were used in the dispersion modelling. The practice of only using a selection of conditions is referred to as using screening level meteorology (RWDI, 2000). The F2 and E3 conditions allow for the determination of a maximum contaminant concentration because the combination of meteorological stability and low wind speed creates minimal diffusion and dilution in the plume.

Descriptions and frequencies of the weather conditions are presented in Table 2.2 (Environment Canada, 1996).

Table 2.2 - Meteorological Conditions

Condition	Stability Class	Wind Speed (m/s)	(km/hr)	Frequency of Occurrence (% of total)	Description
D2	D	2	7.2	6.5	Neutral stability, low wind speed
D5	D	5	18.0	16.8	Neutral stability, moderate wind speed
D10	D	10	36.0	23.5	Neutral stability, high wind speed
E3	E	3	10.8	3.1	Moderate stability, low - moderate wind speed
F2	F	2	7.2	17.8	Stable conditions, low wind speed

2.4 Population Distribution

The pipeline is assumed to be located in central Alberta, southwest of the City of Edmonton. The area is one of beef and dairy farms and a number of hobby farms rather than large grain farms or intensive livestock operations. The population density is approximately 1 family/quarter section of land. One quarter section of land is 160 acres, and has the dimensions of 1/2 mile x 1/2 mile. Assuming that a typical family is 4 persons, the density is taken as 4 people / 648,025m^2 or 6.2 persons per km^2. The area supports recreation with a number of lakes, which are used for their beaches and for both sport and ice fishing. The lake front areas have been developed as summer villages and the local population swells by 500% over the summer months. There are also a number of campgrounds and Provincial parks in proximity to the lakes.

The area is dotted with oil and gas operations. There are single well batteries with associated flare stacks, multiple well batteries, pads of wells from directional drilling, pipeline compressor stations and dehydrators and salt-water disposal wells; these operations are checked daily by operators and some of the facilities house small office complexes.

Children are bussed to local schools. The normal capacity of a typical school bus is 66.

Locations of future or proposed pipelines are limited by the pre-existence of schools, urban centres or public developments through legislated setbacks which provide for the maintenance of an appropriate exclusion zone around sour facilities. Individual residences can be located as close as 100m to a sour facility or pipeline, under current setback policy (AEUB, 2000).

3.0 Hazard Identification and Assessment

The principal hazard associated with the rupture of a sour gas pipeline is the toxicity of the hydrogen sulfide released into the atmosphere. The public health effect of an H_2S release is a potential lethal exposure to humans. The EUB classifies H_2S pipelines in the Province by the quantity of sour gas that would be released at the time of a failure incident (AEUB, 2001). The quantity is calculated as the molar % of H_2S in the pipeline multiplied by the pipeline volume, at operating temperature and pressure and incorporating the compressibility factor. The compressibility factor is calculated from the pressure and temperature factors including critical pressure (P_c) and reduced pressure (P_R) and critical temperature (T_c) and reduced temperature (T_R). The reduced temperature is the operating temperature divided by the critical temperature ($T_R = \frac{T}{T_c}$). The reduced pressure is the operating pressure divided by the critical pressure ($P_R = \frac{P}{P_c}$). The critical temperature is the temperature above which, regardless of applied pressure only one phase exists, this is called the fluid state. The critical pressure is that which would suffice to liquefy the fluid at T_c (Moore, 1972 p 21).

The line volume is calculated as the cross-sectional area of the pipe multiplied by the pipe segment length.

3.1 Pipeline Hazards and Frequencies

Pipelines can fail in a number of different ways: a complete guillotine rupture, or a leak, with a jet with vertical or horizontal flow. The failure can be related to corrosion (either internal or external), operator error or valve failure and can occur at any point in the pipe (ERCB, 1990). Emergency shut down valves (line break valves (ESD or LBV)) are typically triggered at 70% of pipeline pressure and are operated by a SCADA (supervisory control and data acquisition) system (Dowsett, 2002). Pipeline failure rate is related to pipe diameter with an increased number of failures in smaller diameter pipe (Arulanandam et al, 1997). Historical statistics collected by the EUB are used in the determination of the failure frequencies. Frequency statistics are listed in Table 3.1 (RWDI, 2000).

Table 3.1 - Frequency Statistics

Description of Failure	Frequency of uncontrolled sour gas release (failures/km yr)
Leak (≤2% of X-area) (ERCB, 1990)	5.42×10^{-3} (RWDI, 2000, ERCB 1990)
Rupture	7.45×10^{-4} (RWDI, 2000, ERCB, 1990)

3.2 General Description of Sour Gas Release Modelled for Risk Assessment

The release modelled in this situation was a mid section guillotine pipeline rupture, where the pipe splits completely through mid-segment allowing two zones for gas release. The rationale behind the selection of this rupture included that:

- the distances affected by the hazard were maximized;
- the data supporting the rupture scenario are subject to less interpretation regarding the volume of gas released. During a guillotine rupture the entire volume of the pipe segment is presumed to be lost; and
- the RWDI contract with the EUB provided data for the rupture scenario.

The frequency of any type of pipeline rupture (based on historical statistics generated by the EUB) is 7.45×10^{-4} failures/km-yr; (0.000745 ruptures per kilometer of pipe on an annual basis) (Concord, 1993). This frequency provides an estimate of the maximum annual chance of a pipeline rupture. While ruptures occur less frequently than leaks, they typically result in larger releases than leaks, with guillotine ruptures resulting in the largest geographic area being affected - the hazard area. The difference between a leak and a rupture is the cross-sectional area of pipe that is involved. In a leak the failure area (hole) is only a small percentage of the total cross-sectional area of the pipe. In the case of a rupture the integrity of the pipe is completely lost with the initial hole size failing into a complete pipe break, and two ends of complete pipe cross-section are open to release the pipe contents.

3.2 Gas Compositions

Two gas compositions were modelled one containing 2.5% H_2S and the other containing 30% H_2S. The gas compositions used are representative of a range of sour gas compositions in Alberta (RWDI, 2000). The segment lengths between ESD valves were modelled at 500m, 1000m, 2500m, 5000m, 10000m, and 20000m. The increased segment lengths allowed for the representation of all 4 levels of EUB pipeline classification in the analysis. The EUB hazard classification level is dependent upon the quantity of H_2S released to the atmosphere; these levels are detailed in Table 3.2 (AEUB, 2000) and the gas compositions are detailed in Table 3.3.

Table 3.2 - EUB Level Classification for Pipeline Releases (AEUB, 2000)

AEUB Level	Potential Volume of H_2S Released from Pipe Segment
1	Less than $300m^3$
2	$300 - 2000m^3$
3	$2000 - 6000m^3$
4	Greater than $6000m^3$

Table 3.3 - Representative Gas Compositions (RWDI, 2000)

Component	Mole fraction of component in 2.5% H_2S gas	Mole fraction of component in 30% H_2S gas
Water H_2O	0.0000	0.0000
Helium He	0.0004	0.0010
Hydrogen H_2	0.0002	0.0010
Nitrogen N_2	0.0160	0.0020
Carbon dioxide CO_2	0.0492	0.0800
Hydrogen sulphide H_2S	0.0250	0.3000
Methane CH_4	0.7834	0.5800
Ethane C_2H_6	0.0647	0.0200
Propane C_3H_8	0.0307	0.0060
Iso-butane C_4H_{10}	0.0061	0.0040
Butane C_4H_{10}	0.0107	0.0020
Iso-pentane C_5H_{12}	0.0033	0.0010
Pentane C_5H_{12}	0.0036	0.0010
Hexane C_6H_{14}	0.0033	0.0010
Heptane C_7H_{16}	0.0034	0.0010
Total	**1.0000**	**1.0000**

The gas properties are listed in Table 3.4

Table 3.4 - Gas Properties at Point of Release (RWDI, 2000)

Parameter	2.5% H_2S	30% H_2S
Average Molar mass (kg/mol)	21.4448	31.9604
Standard density (kg/m^3)	0.9070	1.0428
Compressibility @10000kPa	0.6437	0.3727
Operating temperature (K)	278	278
Reduced pressure	2.93	2.3
Reduced temperature	1.33	1.13
Pseudo critical temperature (K)	220.52	259.98
Pseudo critical pressure (kPa)	4801.26	6128.67
Specific heat (J/(kgK)	1854.73	1471.72

3.4 *Dispersion Model*

Dispersion modelling is performed in order to determine the areal extent and concentration-driven magnitude of the hazard. In this case modelling provided the distribution of H_2S concentration downwind of the release. The specific concentration distribution of the H_2S is dependent upon the release rate and the meteorological conditions at the time of the release. The dispersion model used to simulate the pipeline release in this risk assessment is the SLAB model.

The first step in the selection of a dispersion model is to determine whether a gas is buoyant, neutrally-buoyant or dense at source. The buoyancy of the gas refers to its density with respect to air. At expanded atmospheric conditions, mixtures of natural gas with concentrations of H_2S less than 35% are buoyant in air and will rise; natural gas with concentrations of H_2S greater than 35% may be neutrally or negatively buoyant and may travel at ground level or may undergo dense gas slumping effects (Dowsett, 2003). Mixtures of sour gas that are buoyant in air will rise and will disperse higher in the atmosphere, thus reducing the ground level concentrations and the toxicity associated with an exposure. However when a fluid is released from pressurized conditions it is not at standard atmospheric conditions, and it may take some time to reach these final conditions. The understanding of the initial plume buoyancy is critical to public safety. Plumes that are neutrally buoyant or negatively buoyant will travel at ground-level and will have significantly higher consequences. The determination of initial plume buoyancy is highly dependent upon the gas composition and the nature of the system from which it is released. A thermodynamic "flash" calculation is necessary to determine the initial buoyancy flux of a release event (Dowsett, 2003).

SLAB is a Gaussian dispersion model that is a well established and validated approach to estimating the physical dilution of a contaminant emission into the atmosphere. The model is capable of estimating the dispersion of releases with densities less than, equal to, or greater than that of air (RWDI, 2000).

SLAB was developed at the Lawrence Livermore Laboratories (Livermore, California, USA) and is included as a dispersion model by the U.S. EPA in their Risk Management Plan (EPA, 1999). This model can estimate the dispersion of fluids of all densities relative to air; it is the ability to estimate releases that are more dense than air as real (rather than ideal fluids), that gives this model the greatest appeal to regulators (EPA, 1999, RWDI, 2000). Ideal fluids are those that follow the ideal gas law where $\frac{PV}{T} = \text{constant}$, and in pipeline rupture scenarios real fluids may be gases with entrained liquids.

Integral to the dispersion estimation are algorithms that calculate gravity slumping, decreasing density with increasing height, and the thermodynamics of the phase changes within the plume (RWDI, 2000). These calculations are external to the SLAB model and can be performed using either ideal or real gas behaviour assumptions. SLAB requires input batch files that have already calculated the initial mass release rate and temperature profiles at atmospheric conditions. For fluid releases that are as dense as air or lighter than air, SLAB utilizes a Gaussian plume dispersion model; the dispersion model to be used is determined by the in-plume criteria (RWDI, 2000).

For hazard modelling purposes, screening-level meteorology is used to represent a broad range of atmospheric conditions that may be experienced in a region. Screening level meteorology involves only using the predominant conditions in order to achieve a range of hazard or contaminant extents. The range of atmospheric conditions selected is intended to bracket (i.e., bound) the weather conditions found within a local setting (RWDI, 2000). For purposes of conducting screening-level hazard and risk assessments, the parameters used to characterize atmospheric stability and mechanical turbulence in the atmosphere are represented using the Pasquill-Gifford scheme. The details of the Pasquill-Gifford classification system were explained in Section 2.3 - Meteorological Data.

In order to utilize low wind speed, stable atmospheric conditions as screening level meteorology (e.g. F2), the plume spread in the vertical (σ_z) and horizontal (σ_y) directions are mathematically limited to the same degree during the development of the Gaussian plume within the dispersion model. This limiting is called coupling, and results in minimal spread in either the vertical (σ_z) and horizontal (σ_y) directions and maximum spread in the linear distance (σ_x) from the source. If the plume spread was not limited in the vertical (σ_z) and horizontal (σ_y) directions, the plume may have a lesser longitudinal extent. Within the plume there is a conservation of contaminant mass so if there is limited growth in two of the three directions, the growth in the remaining direction is maximized. Maximizing the longitudinal growth of the plume allows for the determination of the maximum distance to a fixed concentration. Often, the atmosphere exhibits a de-coupling of these parameters, where the plume does not develop equally along all three axes (Dowsett, 2002). The use of selected Pasquill-Gifford coefficients results in a prediction of a worst-case release event (i.e. the maximum distance to a fixed concentration).

SLAB is an appropriate tool for dispersion modelling for emergency planning because, by using a range of meteorology, a maximum hazard extent can be determined. For the forensic validation of an actual H_2S release, real time meteorology is used in the determination of an actual exposure assessment.

3.5 Extra Volume and Transient Release Model

Pipeline failures are either ruptures or leaks. (The difference between a rupture and a leak is determined by the percentage of the cross-sectional area of the pipe which has lost its integrity (ERCB, 1990).) Ruptures, which are catastrophic failures, result in large volumes of gas being released in a relatively short period of time. Ruptures are detected either through supervisory control and data acquisition (SCADA) systems or by pressure detection monitors that detect when the pressure in the pipeline drops below a pre-set minimum pressure. Consequences of failures can be minimized by the isolation of the failed segment through the closure of the line break valves. Pressure detection monitors or the SCADA system may detect large leaks. Smaller leaks, such as pinhole leaks, may go undetected for several days or may be detected through either regular inspections or public odour complaints. Leak events result in smaller hazard extents than ruptures because H_2S is released at a lower rate.

In the case of a catastrophic pipeline failure, the failure will result in a time-varying discharge of material (blowdown) from the pipeline. The release of gas is a transient process which typically lasts from several minutes up to an hour, depending upon pipeline characteristics. Pipeline characteristics include - operating pressure of the pipeline, its size, configuration and location of the rupture along the pipe segment, the properties of the fluid, and the length of pipeline segment which can be isolated. For rupture events, a blowdown is characterized starting at a high initial mass flow rate, which decreases rapidly. The length of the pipeline segment discharging fluid dictates the rate of this decrease. As mass is released from the pipeline, the properties of the fluid (e.g., temperature, liquid mass fraction and density) change rapidly in response to the changing pressure conditions (RWDI, 2000).

Under normal operating conditions the fluid being transported in the pipeline is in a gaseous state. If a rapid depressurization occurs, as in a pipeline failure, the thermodynamic properties of the fluid change significantly. When the fluid is released to the atmosphere during the depressurization it expands rapidly (Dowsett, 2002). The pressure and temperature changes cause phase changes in the fluid causing condensation of any vapour entrained in the gas. The SLAB model requires source properties at atmospheric conditions, therefore the thermodynamic changes in the fluid must be calculated as a batch input file. The program input files calculate the time varying properties (i.e. enthalpy, entropy and temperature) in the pipeline as the pressure decreases, and models the thermodynamic properties for use in the dispersion model.

RWDI has developed a transient release modelling program which combines the fluid properties at atmospheric conditions with the mass release profile, in order to more accurately calculate the quantity of gas release during a failure event. This program is run as a batch input file and is not part of the SLAB program. RWDI calls this proprietary program the Transient Risk Assessment Model for Pipelines (RWDI, 2000). Historically, a factor of 1.3 has been applied to pipe segment volumes in order to account for the gas which passed through the LBVs prior to their triggered closure (ERCB, 1990). The volume of gas released from failures in shorter segment lengths of pipe (0.5 - 5 km as compared to 10-20km) is greater than the additional 30% previously proposed (RWDI, 2000). A table of extra mass factors is included in Section 5.5 Interpretation of Results. The extra mass factors for the segment lengths for the 202.7mm ID pipe used in this assessment have been incorporated into the volume calculation.

4.0 Toxicity Assessment

4.1 General and Acute Toxicity

Hydrogen sulfide, H_2S, is acutely toxic to both humans and animals; but over a range of concentrations it can have a range of effects. H_2S is detectable as an odour between 10 and 100ppb (PCF, 2000). The range of effects from being a local irritant to a systemic poison are detailed in Table 4.1 - Effects of H_2S on People.

Table 4.1 - Effects of H_2S on People (PCF, 2000)

Concentration Range (ppm)	Effects
1-10	Moderate to strong odour. Some people may experience nausea, eye tearing and headaches following prolonged exposure. All symptoms are reversible; hypersensitive individuals within the population may respond more severely.
10-20	Strong and offensive odour. Increased lung and eye irritation.
50 - 100	Burning sensation in the eyes and throat, headaches. A temporary loss of smell may occur in some individuals.
100-250	Progression of the symptoms of the irritation of the eyes and upper respiratory tract becoming more severe. Upper respiratory tract irritation may lead to bronchitis. Most individuals lose their sense of smell.
250	Continued exposure causes pulmonary edema (lung tissue swelling and filling with fluid) and keratoconjunctivitis (swelling of the eyes and eyelids).
500	Victim is knocked down (loss of sense of balance and reasoning). Respiratory disturbance requiring resuscitation occurs in 2-15 minutes. Victims lose consciousness rapidly and breathing stops, immediate rescue is required to prevent death.
750	Rapid unconsciousness, cessation of breathing and death without immediate rescue.

Regulatory levels of exposure are summarized in Table 4.2.

Table 4.2 - Summary of Regulatory Exposure Levels and Guidelines

Concentration (ppm) and Time Limit	Organization
0.01 for 1 hour average	Alberta Ambient Air Quality Guidelines (based on odour) (Alberta Environment, 2000)
0.003 for 24 hour average	Alberta Ambient Air Quality Guidelines (based on odour) (Alberta Environment, 2000)
1.0	Alberta Health (Alberta Health, 1988) voluntary evacuation for sensitive individuals
5.0	Alberta Health (Alberta Health, 1988) voluntary evacuation for individuals without pre-existing health concerns
10.0	8 hour occupational exposure limit (Alberta Human Resources and Employment, 1998)
15.0	15 minute occupational exposure limit (Alberta Human Resources and Employment, 1998)
20.0	Ceiling occupational exposure limit (Alberta Human Resources and Employment, 1998)
20.0	Alberta Health (Alberta Health, 1988) urgent mandatory evacuation
30.0	American Institute of Industrial Hygienists ERPG-2 Emergency Response Planning Guidelines. Allows maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing irreversible or serious health effects.
50.0	US National Academy of Sciences EEGL Emergency Exposure Guideline Level. A concentration that is judged to be acceptable and that will allow individuals to perform specific tasks during emergency conditions that last 1 hour. (EPA, 2000)
100.0	EUB basis for establishing emergency planning zones around facilities based on an assumed 30-minute exposure.
100.0	American Institute of Industrial Hygienists IDLH (immediately dangerous to life or health - 30 minute exposure) (NIOSH, 1996)

4.2 *Probit Analysis*

Both duration of exposure to H_2S and the exposure concentration influence the response of an exposed individual. The combination of exposure time and concentration is known as the toxic load; the relationship is not linear rather it takes the form $L = C^n t$ where C is concentration, t is time and n is the exponent applied to the concentration (Rijnmond Public Authority, 1982, Rogers, 1990). The value of "n" is currently taken as 2.5 in the Triple Shifted Rijnmond equation used by the EUB. The value was assigned through interpretation of toxic load dose response curves and their application to known fatalities (RWDI, 2000, Rogers, 1990). Different equations from different jurisdictions assign different values to the exponent "n".

As the exposure concentration increases, the amount of time to produce a given injury decreases rapidly (Rijnmond Public Authority, 1982). The exponent applied to the concentration term accounts for the greater role played by concentration in the non-linear relationship. The load equations were developed based on a constant concentration exposure in a lab-type environment, rather than a fluctuating load as may be experienced in a real incident (Rijnmond Public Authority, 1982).

The toxic load is combined with other parameters including inter- and intra-species variations into a probit equation (Guo, 2001). The probit equation linearizes the relationship between proportion of population responding and toxic load (Klaassen, 2001, Finney 1971). The probit equation is a standard model for relating toxic response to acute agents and in this case it is given by:

$Y = a + b*Ln(L)$

The plotting of the equation, where Y is the probit for the proportion responding and L is the toxic load, assumes a lognormal distribution which represents the population's response to acutely toxic gases. The parameters "a" and "b" are empirical constants for fitting the linear relationship to the transformed experimental data, but some interpretation on the meaning of these constants can be suggested. The parameter "a" reflects the inter-species variability; the difference between humans and animals that is expressed as a factor which can influence either the concentration or the exposure term (Guo, 2001). The parameter "b" is a measure of the intra-species variability, the differences in susceptibility amongst a single species (humans) (Guo, 2001). The probit method (Finney, 1971), established before hand held calculators were widely available, arbitrarily sets a value of 5 (to avoid negative values) to the median population response, that is 50% of the population will respond and 50% will not for a given toxic load. In the case of an acutely toxic gas the probit value of 5 corresponds to the LC_{50} (Guo, 2001). Each standard deviation departure from the median represents a probit of 1 (Klaassen, 2001, Finney, 1971). (i.e. The median response plus one standard deviation would have a probit value of 6 and would encompass a response of 84.1% of the population; the median response minus one standard deviation would have a probit value of 4 and would encompass 15.9% of the population (Klaassen, 2001)). A summary relationship between the percentage of the population responding and the corresponding probit value is presented as Table 4.3 (Rijnmond Public Authority, 1982).

Table 4.3 - Relationship between Probit and Percentage Affected

% of Population Affected	Probit Value
0.1	1.91
0.5	2.42
1	2.67
5	3.36
10	3.72
20	4.16
40	4.75
50	5.0
60	5.25
80	5.84
90	6.28
95	6.64
99	7.33
99.5	7.58
99.9	8.09

4.3 *Triple Shifted Rijnmond Equation*

The probit equation adopted by the EUB for calculation of population response is the Triple Shifted Rijnmond Equation. The original Rijnmond equation (Rijnmond Public Authority, 1982) was generally accepted as a reasonable first order representation of H_2S exposure and fatalities. The EUB initially changed the "a" term to reflect a sub-population of more sensitive individuals by replacing the LC_{10} in the original equation with the LC_{50} for the sub-population, thereby shifting the original Rijnmond equation to be more cautious (RWDI, 2000). The equation was then shifted further; again by manipulation of the "a" term to assure that fatality predications would include available published experimental (and anecdotal) evidence and exposure guidelines yielding the Triple Shifted Rijnmond equation (Rogers, 1990). The numerical values in the equations are detailed in Table 4.4.

Table 4.4 - Numerical values for the Rijnmond Equations

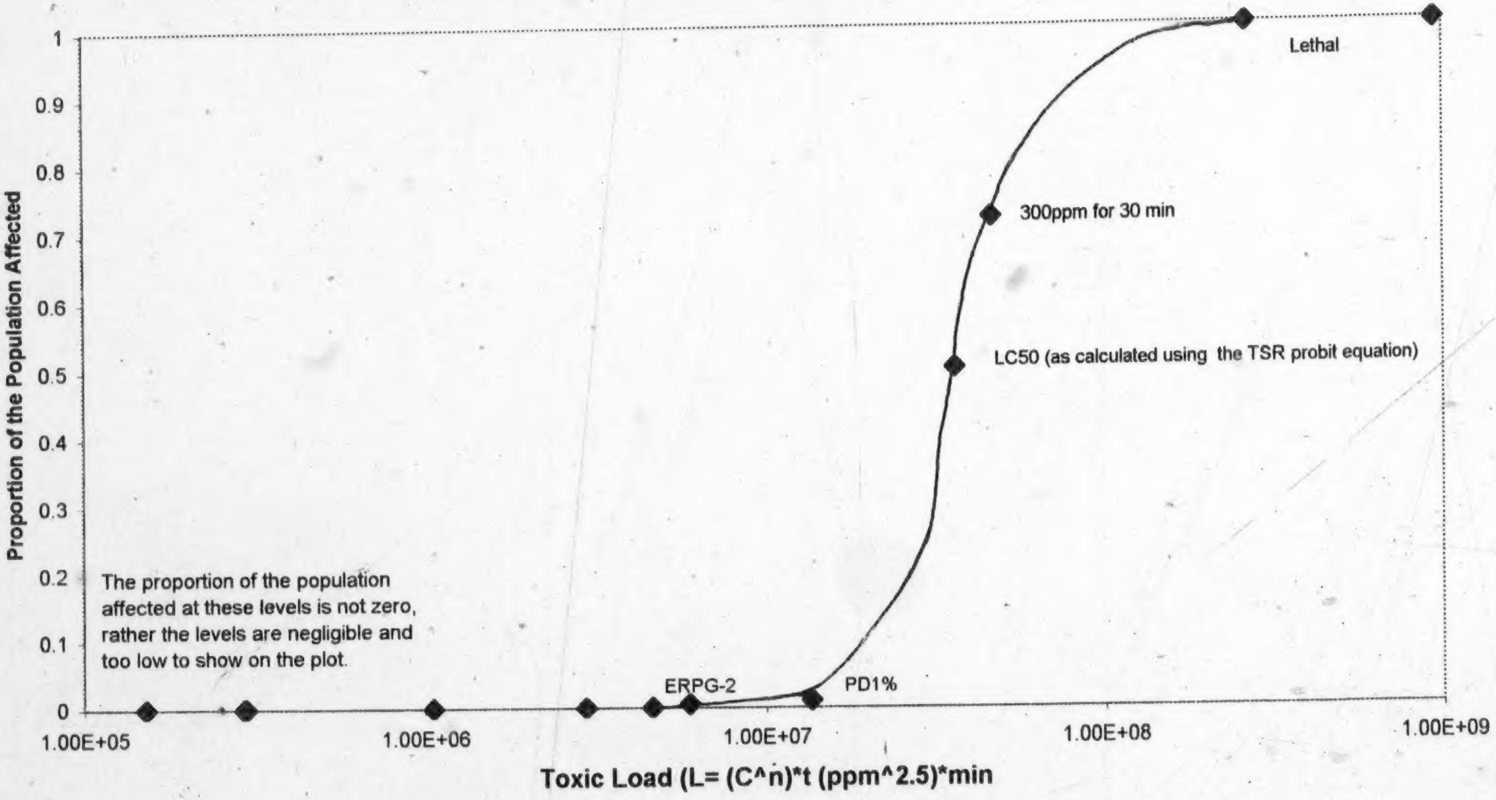
	Equation
Original Rijnmond equation	probit $= -41.48 + 2.366 \ln (C^{2.5}t)$
Shifted Rijnmond equation	probit $= -39.80 + 2.366 \ln (C^{2.5}t)$
Triple Shifted Rijnmond equation	probit $= -36.20 + 2.366 \ln (C^{2.5}t)$

The toxic load, probit values (as calculated by the Triple Shifted Rijnmond equation), and corresponding percentage of the population affected for some exposure guidelines are presented as Table 4.5 and Figure 4.1.

Table 4.5 - Development of an Exposure/Effects Curve

Exposure Guideline	**Corresponding Toxic Load ($ppm^{2.5}min$)**	**% of population affected**
Alberta Human Resources Management 15ppm for 15 min	1.31×10^4	Negligible
Alberta Human Resources Management 10ppm for 8hr	1.52×10^5	Negligible
ERPG-2 30ppm for 1hr	2.96×10^5	Negligible
100ppm for 3 minutes	3.00×10^5	Negligible
EEGL 50ppm for 1hr	1.06×10^6	Negligible
AEUB EPZ 100ppm for 30min (also NIOSH - IDLH)	3.00×10^6	Negligible
ERPG-3 100ppm for 60 min	6.00×10^6	0.05
Probability of Lethality of 1% (Triple Shifted Rijnmond Probit Equation)	**1.36×10^7**	**1.0**
LC_{50} 500ppm for 6.5min	3.63×10^7	50
300ppm for 30min	4.68×10^7	72
Lethal (Lewis, 1992) 600ppm for 30min	2.65×10^8	100

Figure 4.1 - Proportion of Population Affected vs Toxic Load
(Exposure Guidelines where the load and probit are calculated using the Triple Shifted Rijnmond Equation)



4.4 Other Probit Models

Other organizations have developed alternative toxic load models for the response of the population to hydrogen sulfide. The probit model adopted by the Centre for Chemical Process Safety (CCPS, 1989) is:

Probit = -31.42 + 3.008 ln(L) where Toxic Load $L = C^{1.43}t$ Equation (1)

The Triple Shifted Rijnmond equation is:

Probit = -36.30 + 2.366 ln(L) where Toxic Load $L = C^{2.5}t$ Equation (2)

The CCPS and the Triple Shifted Rijnmond probit equations are similar in mathematical structure for their assessment of population response as indicated in Table 4.6 (adapted from Hilderman and Wilson, 2000), but the proportion of the population affected corresponds to a lower toxic load for the CCPS equation.

Table 4.6 - Comparison of Probit Equations

Population Response	Probit	Equation	Toxic Load
50%	5	CCPS	1.81×10^5
		TSR	3.65×10^7
10%	3.72	CCPS	1.18×10^5
		TSR	2.13×10^7

Using the LC_{50} criteria from the TSR equation (500ppm for 6.5 minutes which using the TSR equation equates to a toxic load of 3.65×10^7) and substituting the same concentration and time values into the CCPS probit equation, yields a probit value of 0.942 which equates to <0.1% of the population being affected. The power (exponent) function difference between the TSR and the CCPS equations accounts for the differences in the calculation of the toxic loads.

The EPA has proposed Acute Exposure Guideline Levels for hydrogen sulphide, these are currently in a draft form for public review. The guidelines propose three different levels of exposure classification and suggest a toxic load exponent of n=4.36 (EPA, 2000). The inter- and intra- species uncertainty factors are each estimated at 3 and are multiplied together to yield an approximate uncertainty factor of 10, which is applied to the concentration term in the scaling of the equation from animal to human exposure loads (EPA, 2000). The application of this uncertainty factor to the concentration term alone, gives an overall uncertainty factor of $(10)^{4.36}$ = 22,909 on the toxic load. Toxic Load = $C^n t$, by applying the uncertainty factor to the concentration term the equation becomes Toxic Load = $(C*UF)^{4.36}t$ or $(Cx10)^{4.36}t$, effectively applying an uncertainty factor of 22,909. Alternatively if the uncertainty factor is applied to the entire toxic load term $(C^{4.36}t)*10$ the intent of the individual inter- and intra-species uncertainty factors is maintained (Hilderman et al., 2000). The argument in favour of applying the uncertainty factor to the concentration term has been based on the normal practice for applying uncertainty terms in risk assessment. The arguments, however, do not acknowledge the impact of the non-linearity introduced by the toxic load concept.

The peer review of this toxic load equation by others in the scientific community has suggested that an overall uncertainty factor of 10 be applied to the toxic load term, not just the concentration term, in order to bring the AEGLs in line with other probit models (Hilderman et al., 2000).

4.5 Natural Gas Toxicity

During a pipeline failure hydrogen sulfide is released into the atmosphere with natural gas, a mixture rich in light end hydrocarbons. Natural gas itself can present health hazards with prolonged or extreme exposures; including explosion or fire and oxygen displacement (Drummond et al., 1996). In a mixture of H_2S and natural gas, it is the concentration of the H_2S that determines which of the two components is the most hazardous. When the H_2S concentration is less than 0.4% or 4000ppm the hazards associated with the mixture are those of hydrocarbon stream - those hazards are fire or explosion, hydrocarbon toxicity and oxygen deficiency (where the available air is displaced by hydrocarbons). In mixtures where the H_2S is greater than 0.4% (4000ppm) the principal hazard of the gas is H_2S toxicity (Drummond et al., 1996).

4.6 Tolerable Daily Intake (TDI)

Hydrogen sulphide is not considered to be a carcinogen (EPA, 1987). For substances that are not carcinogens or mutagens, it is normally assumed that there is a level below which no harmful effects will occur, effectively a threshold on the dose-response curve. This level of exposure is called the NOAEL; the no observed adverse effect level. The level is set after examination of the toxicological literature and is subject to ongoing review. The tolerable daily intake (TDI) in Canada or the reference dose (RfD) in the United States is derived from the NOAEL and made applicable to general human populations (not sensitive sub-populations) through the application of uncertainty factors (Thomas and Hrudey, 1997). The NOAEL exposure level is reduced to the TDI by dividing the NOAEL by the product of the uncertainty factors. The uncertainty factors generally range between 1 and 10 and account for:

- extrapolation from experimental animal species to humans;
- the variability of sensitivity within the population to account for more sensitive individuals;
- inadequacies in the experimental data including lack of data on developmental, chronic or reproductive toxicity, or reliance on a LOAEL (lowest observed adverse effects level);
- evidence of an additive or synergistic interaction with another substance in the environment (Meek et al., 1994).

The uncertainty factors can reduce the NOAEL by a factor of between 100 and 1000. If the uncertainty factors are greater than 10,000 the toxicology data may not be complete or reliable enough to set a TDI (Thomas and Hrudey, 1997).

The TDI or RfD is an estimate of a continuous exposure (inhalation in the case of H_2S) to the human population that is likely to be without an appreciable risk of deleterious non-cancer effects, considering all other toxic effects, throughout a lifetime. Thus this is a criterion set for chronic not acute exposure (Thomas and Hrudey, 1997).

Canada does not have a TDI level set for H_2S. The RfD for H_2S is currently under review by the US Environmental Ageney (EPA). The sub-chronic animal study selected for derivation of the inhalation RfD is Brenneman et al. (2000), a study of the nasal mucosa of rats subjected to sub-chronic inhalation of hydrogen sulfide. Further work has been performed by Dorman and Kimbell (2002) relating

H_2S exposure to the incidence of lesions within the rat olfactory epithelium to substantiate the Brenneman findings. The critical effect (nasal lesions of the olfactory mucosa) was reported to occur at a LOAEL of 30ppm and had a NOAEL of 10ppm. The rats were exposed to concentrations of H_2S of 0 - 80ppm for 6 hr/day, 7days/week for 10 weeks. The NOAEL and the LOAEL were converted from mass of contaminant per volume of air (mg/m^3 = ppm*(MW/24.45) where MW = 34.06g/mol) to give a NOAEL and LOAEL of $14mg/m^3$ and $42mg/m^3$ respectively. These values are converted to a continuous exposure by multiplying by a factor of 6hours/24hours to give a NOAEL of $3.5mg/m^3$ and a LOAEL of $10.5mg/m^3$ (these values are for rats). The inhalation experiments were performed on rats and there is a difference between the ventilation rate of rats and humans. In order to obtain the human equivalent concentration the values were multiplied by the ratio of the rat:human extrathoracic surface area and the rat:human ventilation rate. The resulting factor used to determine the human equivalent concentration was 0.184. The human equivalent concentrations for the NOAEL and LOAEL are 0.64 mg/m^3 and 1.9 mg/m^3 respectively. In order to calculate the RfD, the NOAEL was divided by an uncertainty factor of 300 to yield an RfD of 0.002 mg/m^3 or 0.001ppm or 1ppb (EPA Draft, 2002). The uncertainty factor of 300 is derived through the product of a factor of 10 for the intraspecies variation, a factor of 10 for the study being a chronic (not a sub-chronic) study and a factor of $3(\approx \sqrt{10})$ because of the use of a dosimetric adjustment from rat to human. The details herein are taken from the EPA external review draft of the Toxicological Review of Hydrogen Sulfide (and IRIS summary) (2002). In order to accurately summarize the regulatory limits of H_2S and to identify the proposed levels, the inclusion of the details from the draft EPA were required to portray a complete data set. There is no legal or regulatory requirement that the EPA will adopt these levels, and no claims are being made regarding the final position of the EPA and the details in the draft document.

Alberta Health has recently performed a review of the health effects associated with short-term exposure to H_2S (Alberta Health and Wellness, 2002). The review concluded that young normal healthy adults can tolerate up to 10ppm H_2S without significant effects, but that concentrations of 2ppm can cause bronchial obstruction in asthmatics. The Alberta Health study concentrated on short-term exposures while the Brenneman et al. (2000) study, which formed the basis of the EPA's draft document, concentrated on longer-term exposures. The Alberta Health study has been criticized regarding the number and the quality of the toxicological studies from which conclusions were drawn (Guidotti, 2002). Only 15% of the 45 studies met the high confidence index ranking in the quality criteria established for the review (Alberta Health and Wellness, 2002).

The implications of the proposed revised USEPA RfD, the lack of a Canadian TDI and the Alberta Health study, are that there remains considerable uncertainty in the toxicology of H_2S and the health effects. The toxicology of H_2S is an area requiring additional review. The toxic load as opposed to the exposure concentration provides a means for the determination of a dose response curve when presented in concert with a probit equation. While the acute effects of high exposures are clear, the effects of low dose exposures and the points at the lower end of the toxic load scale (near negligible proportion of the population affected) required further understanding. That Canada does not have a TDI for H_2S, apparently reflects the localization of the concern about industrial exposure to H_2S (predominantly in Alberta and other oil producing areas). This rationale ignores the other sources of H_2S exposure such as sewage treatment and agricultural waste management which are common across Canada.

4.7 Odour Implications and Thresholds

Figure 4.2 is a graphical representation of a panel assessment performed by the Ontario Ministry of the Environment (OME, 1989 and Nagy, 1991). The figure shows the increasing concentration of H_2S (to a maximum of 1ppm) and the population response. The interpretation of this data is for individuals located in their yards or on their property at the time of odour detection. The implication of sheltering, and the detection of gas levels in the home are not included in this discussion. If there was H_2S gas at an ambient concentration of 0.36ppm in the home, the concentration outside could conceivably be significantly higher due to the sheltering effect of the home.

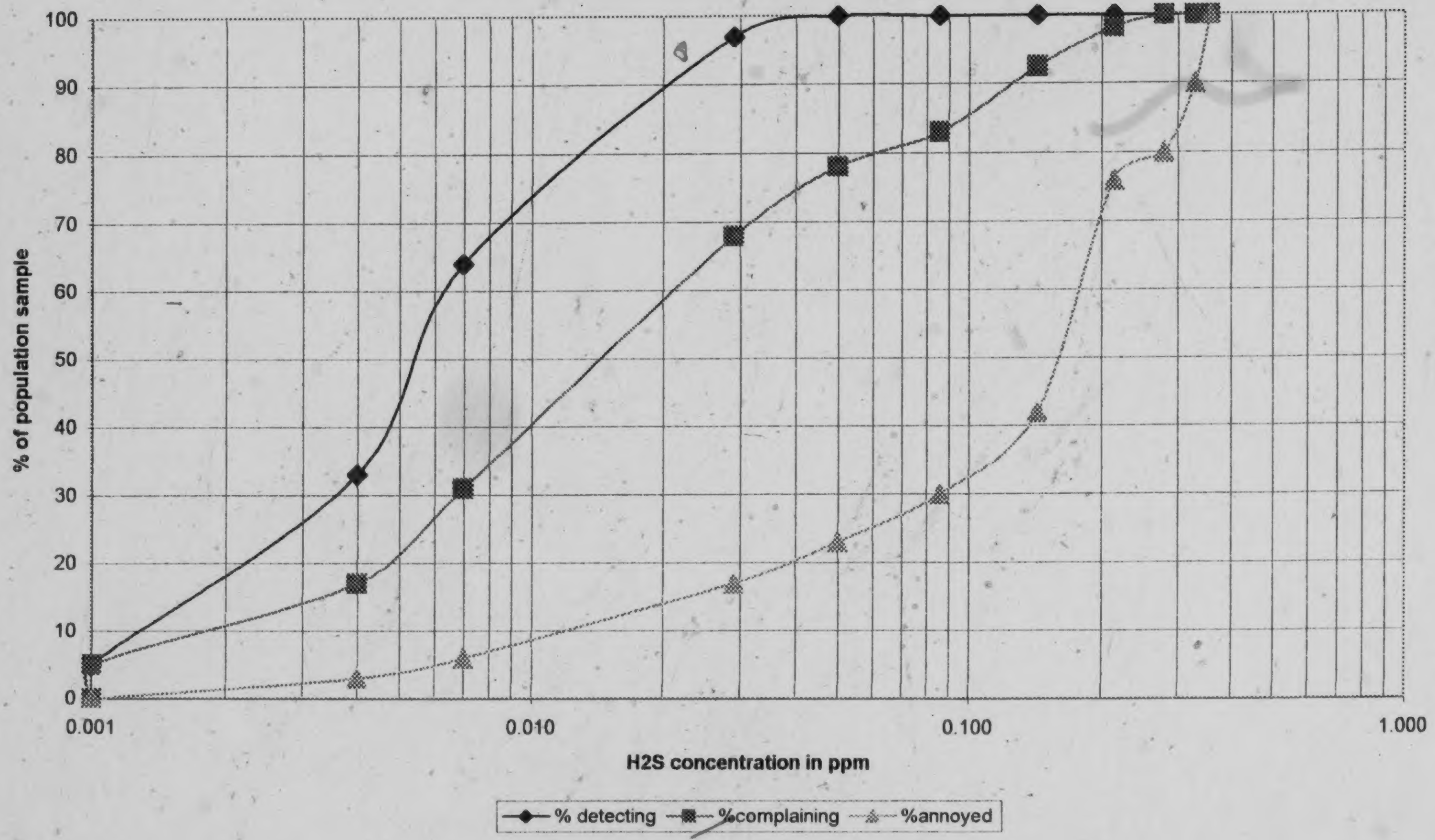
The responses were grouped into three classifications:

1. the level when the person could detect an odour attributable to H_2S gas (detection level);
2. the level at which the person was sufficiently annoyed that they would initiate a complaint about the gas odour (complaint level); and
3. the level at which the person would initiate actions, on their own, to be away from the odour i.e. leave their property (annoyance level).

At a level of 0.36ppm H_2S the 100% of the responding population indicated that they would be sufficiently annoyed by the odour that they would leave their property (OME, 1989 and Nagy, 1991). The implication of an H_2S odour of 0.36ppm causing self-evacuation is that as long as the evacuation was in the correct direction (away from the source, in the direction of the prevailing wind) the exposure may be minimal and the health effects incurred would be reversible. Shusterman (1992) presented summary data of population response to odour (from three separate reports, none of which was the OME or the Nagy study); the results were modified and presented in Dorman et al., 1999 showing similar distinct population responses to odour as detailed in OME, 1989 and Nagy, 1991.

At an ambient concentration of 0.36ppm H_2S (0.5 mg/m^3 or 500$\mu g/m^3$) the population response graph indicates that 100% of the population would be sufficiently annoyed at the odour of H_2S that they would initiate actions on their own to be away from the odour (i.e. evacuate). The human equivalent LOAEL is 1.34ppm H_2S (1.9 mg/m^3 or 1900$\mu g/m^3$) (Brenneman et al., 2000), if self evacuation occurs at 0.36ppm then essentially there is a self preservation mechanism built into the olfactory detection of H_2S because this concentration is so far below a toxic level.

Figure 4.2 - Population Response to H2S Odour (Nagy, 1991)



5.0 *Exposure Assessment*

In order to complete a risk assessment, once the issues have been identified and the hazards have been identified and assessed, the potential exposure of the receptors to the hazard must be assessed.

The selection of a criterion for public safety planning must consider both the nature of the hazard and the level of protection desired. In the establishment of emergency planning zone boundaries, the criterion selected should address the immediate short-term needs of the public at the time of an accident (RWDI, 2000). The data for the entire criteria detailed can be obtained from the output of the SLAB dispersion model; those to be considered include (RWDI, 2000):

Concentration Limits – An emergency planning zone boundary may be established using a criterion that defines an exposure to a specific pollutant concentration level, without regard to exposure time. An exposure to 100ppm H_2S is the current standard utilized by the EUB for establishing emergency planning boundaries for unignited sour gas release events (AEUB, 2002). The distance to this criterion has been predicted for safety scenarios using dispersion modelling.

Equivalent Toxic Exposure Limits – Emergency planning zone boundaries may be established using criteria that consider the level of toxicity associated with an exposure. The toxicity associated with an exposure can vary depending upon the concentration to which a person is exposed (e.g., a steady or time-varying profile) and the duration of an exposure. A measure of toxicity can be calculated using the toxic load method which provides a means of incorporating both concentration and time to compare a given exposure to other known, published toxicity guidelines.

Results obtained from toxic load calculations provide a comparative means to review a specific exposure and exposure duration.

Probability of Fatality Limits - Emergency planning zone boundaries may also be established using criteria that consider a defined toxicological outcome. The probability of fatality for people exposed to H_2S as determined using the Triple Shifted Rijnmond (TSR) equation was discussed previously in Section 4.3. An estimate of the distance at which the probability of fatality falls below one percent is used as a measure by which emergency planning zones may be established. This fatality probability presumes that conditions allow someone to be located at the specified location for the specified duration.

The TSR equation is used as the outer bound for plausible level of fatality. The TSR equation was intentionally biased towards caution so that it would most likely overestimate the expected adverse outcome for any H_2S exposure scenario. The TSR equation is not intended to give the most likely outcome, but rather it is intended to bound the upper extreme of what might happen. If 100 people were standing at a location in the plume at a distance corresponding to that of a 1% probability of fatality, it is unlikely that the even one person would die. It would be even rarer to have 100 people at the distance where the 1% level of fatality exposure would occur. Thus, because of the number of people exposed to the maximum concentration at the distance corresponding to a probable risk of fatality of 1%, the rare event circumstances and the TSR representing the outer plausible bound for fatalities, the 1% distance is judged to be beyond a distance at which fatalities would be reasonably expected to be caused by a release event. Thus, despite the title

"1% level of fatality", the corresponding distance is one where no fatalities would reasonably be expected.

An "Equivalent Toxic Load Limit" is considered, by both the EUB and Alberta Health and Wellness, as a reliable and appropriate means for establishing emergency planning zone boundaries (AEUB, 2002, Alberta Health and Wellness, 2003). The use of this criterion provides a consistent means for selecting the level of protection desired and for comparing various release events, configurations and durations. The use of toxic load criterion is consistent with evolving regulatory philosophy and requirements, which suggests that the selection of emergency planning criteria should consider both the level and the duration of the exposure (AEUB, 2001).

The use of a criterion based strictly on concentration (as opposed to a criterion in which both concentration and exposure time are considered) does not address the level of protection desired. It has historically been assumed that the selection of criterion based strictly on concentration will result in the maximum hazard extents. This is not always the case, in some long-duration release events, the hazard distances calculated using an equivalent exposure method could exceed those calculated using criterion based strictly on concentration (RWDI, 2000). Thus, the use of criterion based strictly on concentration may not result in consistent public safety decisions.

As risk assessments on pipelines are completed for emergency planning purposes, the exposure of the receptor population is necessarily hypothetical, modelled based on a series of assumptions and conditions presumed to be occurring at the time of any incident. Forensic modelling is currently being performed by RWDI West Inc. on a project basis by companies who have had releases of H_2S, but because of the confidential nature of the documentation there are no specific references available to be cited. In forensic modelling following an actual release, the spread and development of the H_2S plume can be modelled based on the conditions which actually occurred at the time of the release including: meteorological, topographic, population affected. The forensic models can then determine the receptor exposures. The forensic models also serve to validate the modelling technology by comparing predictions with actual measurements obtained from air monitoring stations during the event. Much of the post-event verification modelling performed by RWDI has indicated that the plume dispersion followed the predicted path as determined by the SLAB plume dispersion model completed as part of the risk assessment and management plan (Dowsett, 2002).

The risk assessment on the generic pipeline was performed using screening meteorology, topography and ground cover as inputs to the SLAB model and the batch files required to model the atmospheric conditions of the gas during the release. The two concentrations modelled were 2.5% and 30% H_2S in gas streams with representative compositions over five meteorological conditions. Each of the concentrations was modelled as being released from six different pipe segment lengths - 500m, 1km, 2.5km, 5km, 10km and 20km. The maximum hazard distance from ruptures of each pipe length was selected from the five meteorological conditions modelled.

5.1 *Model Results - Endpoints chosen for discussion*

The results from the dispersion model give the distances from the source, in the direction of the prevailing wind, that the plume will have travelled before the ground concentration reaches the model endpoint. The SLAB output delivers the maximum concentration (as a volume fraction of the initial maximum concentration) at a downwind distance and the time of the maximum concentration. Through the associated input and output batch files (transient mass release calculation, isenthalpic and adiabatic flash calculation and the mean probability of lethality) the endpoints of concentration, dose (equivalent concentration) and lethality can be calculated (Dowsett, 2002). The programs for the calculation of the endpoints are proprietary information belonging to RWDI West Inc. while SLAB is available in the public domain.

In this risk assessment the **concentration endpoint** is defined as the maximum distance downwind where an exposure to a concentration of 100ppm H_2S, based on a 30 minute meteorological averaging interval, occurs. With average concentration measurements being calculated (from predicted values by the model) every 30 minutes, this is the furthest distance from the rupture site where an individual could encounter an ambient concentration of 100ppm. Some risk assessments utilize 3-minute meteorological averaging conditions. The relationship between averaging times is $\left(\frac{C_1}{C_2}\right)=\left(\frac{T_1}{T_2}\right)^{-0.2}$ where C_1 and C_2 are the concentrations at averaging times T_1 and T_2 respectively (Angle and Sakiyama, 1991, p 4-39). Thus a 100ppm concentration on 3 minute averaging is equivalent to a concentration of

63ppm on 30 minute averaging. Shorter averaging times result in greater hazard distances because of a greater number of data points in the averaging calculation.

Both 3 minute and 30 minute averaging intervals provide hazard distances that are a reasonable basis for public safety planning (RWDI, 2000). The average concentration is predicted on 3 or 30 minute intervals until it falls below 100ppm. The EUB currently requires implementation of an Emergency Planning Zone (EPZ) for sour gas wells at the distance to a concentration of 100ppm H_2S calculated at meteorological conditions of "F2" at 3 minute averaging intervals. Fatalities are not expected to occur at these hazard distances (AEUB, 2002). The EUB uses two different endpoints depending on the origin of the release. If the release is from a sour gas well the EUB considers the concentration endpoint for the planning of an EPZ. If the release is from a pipeline or facility, and the volume of gas released is fixed due to equipment limitations, the EUB considers the dosage or equivalent concentration endpoint in the establishment of an EPZ.

The **dosage endpoint** considers both the concentration and the duration of the exposure. High exposure concentrations or prolonged exposure times are more likely to cause more adverse effects than lower exposure concentrations and shorter exposure times. After a pipeline rupture the concentrations and exposure durations can be variable, calculating an equivalent dosage accounts for variable exposures and includes the influence of both concentration and time. The modelled dosage endpoint chosen for this risk assessment is the point where the equivalent toxic load, concentration integrated over a time period, is equal to a dose of 100ppm for 30 minutes (i.e. $L=C^{2.5}t$; $L=(100)^{2.5}(30)=3.0\times10^{6}\text{ppm}^{2.5}\text{min}$). This toxic load is the EUB basis for establishing emergency planning zones around fixed facilities and pipelines and for the NIOSH (US National Institute of Occupational Safety and Health) IDLH (Immediate danger to life and health) criterion. The endpoint is calculated by integrating the concentration values over the time profile until the equivalent load is attained.

$$\text{Equivalent Toxic Load} = \int_0^T C^{2.5}dt = 3.00x10^6 \text{ ppm}^{2.5}\text{min} \qquad \text{Equation (3)}$$

The equivalent concentration is then calculated using Equation (4).

$$C_{\text{equivalent}} = \left(\frac{\int_0^T C^{2.5}dt}{T}\right)^{\frac{1}{2.5}} \qquad \text{Equation (4)}$$

T is the total time required in order to attain the equivalent toxic load as integrated.

The use of integration allows for the calculation of a cumulative dose using specific concentrations over time, rather than using either an average or a maximum concentration over the entire time period. The equivalent concentration is an estimate of the concentration over the course of a release event and is a comparative tool for differing concentration and time profiles.

In this risk assessment the **lethality endpoint** is the maximum distance from the rupture where the dose would result in a fatality level of 1% of the exposed population, as calculated using the Triple Shifted Rijnmond probit equation. An affected level of 1% of the population corresponds to a probit value of 2.67. When the calculation is performed from the original probit equation included as Equation (1) in Section 4.4:

$$\text{Probit} = -36.2 + 2.366\ln C^{2.5}t$$

the equation becomes

$2.67 = -36.2 + 2.366\ln(L)$ where $L = C^{2.5}t$

which yields a toxic load $L = 13.6 \times 10^6$ ppm$^{2.5}$min.

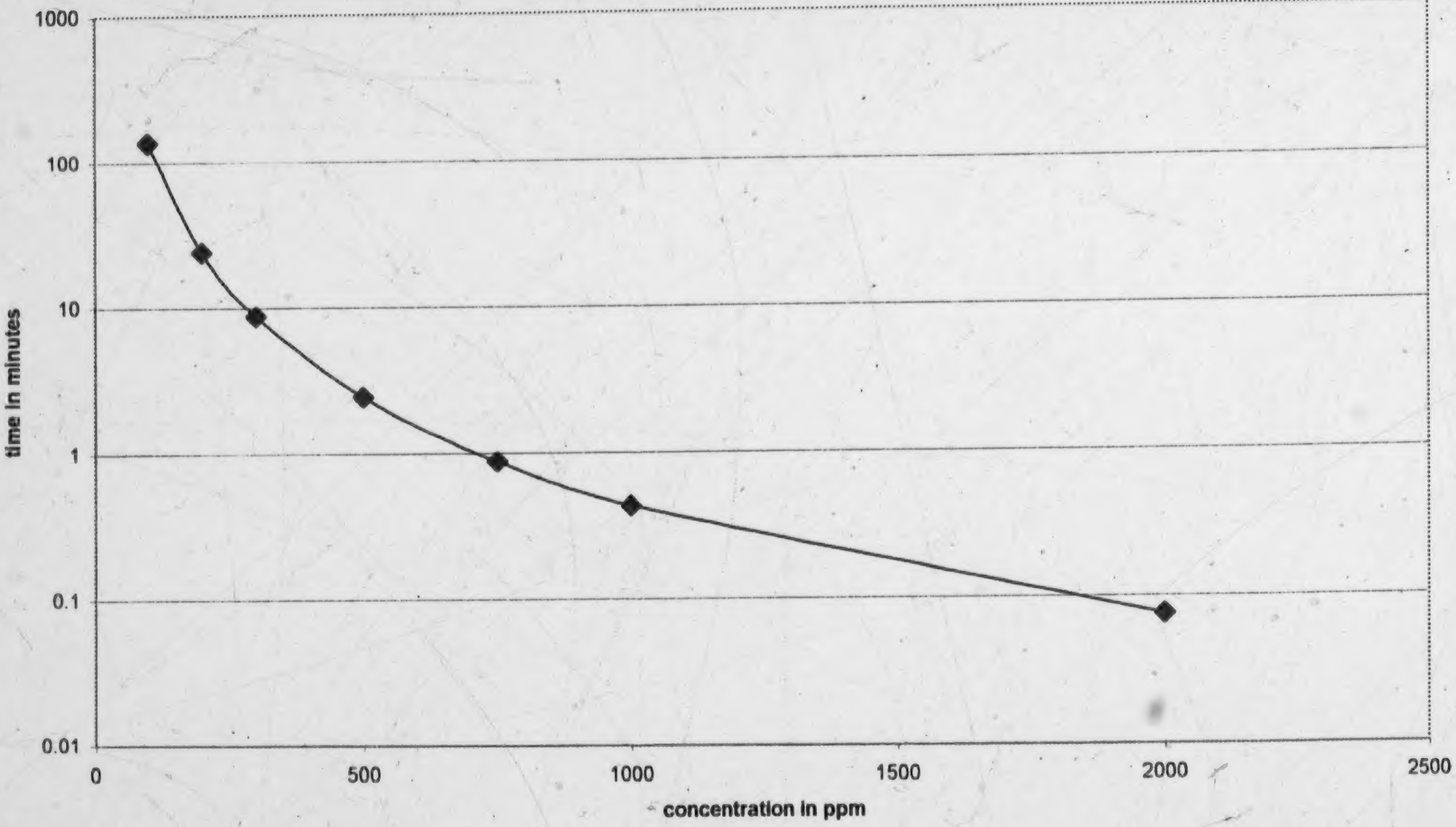
A toxic load of 13.6×10^6 ppm$^{2.5}$min is equivalent to exposure to a concentration of 100ppm for 136 minutes or a concentration of 200ppm for 24 minutes. Table 5.1 provides exposures for the toxic load of 13.6×10^6 ppm$^{2.5}$min (probit 2.67, PD1%). Figure 5.1 is a graphical representation.

Table 5.1 - Equivalent Exposures based on Toxic Load (1%PD for TSR)

Concentration (ppm)	Time (min)	Toxic Load (ppm$^{2.5}$min)
100	136	13.6×10^6
200	24	
300	8.7	
500	2.4	
750	0.9	
1000	0.4	

Of the three endpoints discussed, the lethality endpoint is typically located at a distance closest to the release, the dosage endpoint is further away from the release than the lethality endpoint and the concentration endpoint is the greatest distance away from the release. At the shortest distance from the release the lethality endpoint corresponds to a maximum probability of lethality of 1% (with no fatalities expected in reality), while the endpoint corresponding to the greatest distance from the release is not expected to be associated with any fatalities under any conceivable circumstances.

Figure 5.1 - Equivalent concentration and time exposure for a toxic load based on PD1% (TSR)



The concentration endpoint is for a concentration of 100ppm, thus the plume has developed and time has passed for the concentration within the plume to be at a maximum of 100ppm at that location. As the release is a transient event the concentration of H_2S within the plume will reduce over both distance and time.

The distances from the release to the various endpoints under the varying meteorological conditions are presented in Tables 5.2, 5.3, 5.4, 5.5, 5.6 and 5.7 with data generated by RWDI West Inc. in fulfillment of their contract with the EUB. The data were generated by running SLAB and the various proprietary batch files of RWDI West Inc.

5.2 Concentration Endpoint

The concentration endpoint is the maximum distance from the rupture site where the concentration is 100ppm H_2S. The modelling criterion for the EUB concentration is the meteorological condition F2 where the diffusion and dilution are minimized giving a maximum hazard distance (AEUB, 2002). Table 5.2 shows the maximum distances to the concentration of 100ppm H_2S from a 2.5% H_2S gas release in different meteorological conditions. Table 5.3 shows the maximum distances to the concentration of 100ppm H_2S from a 30% H_2S gas release in different meteorological conditions. The maximum distance to a concentration of 100ppm H_2S for each segment length, as evaluated in the differing meteorological conditions, is indicated in bold. In each case this maximum distance represents the outer boundary of the maximum predictive impact because all of the ground in between the source and this maximum distance will be impacted by the 100 ppm criterion.

Table 5.2 - Distance from rupture to a maximum concentration of 100ppm H_2S from a release of a 2.5% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)** D2	D5	D10	E3	F2
500	260	362	**543**	323	429
1000	284	401	**652**	363	595
2500	305	438	757	398	**813**
5000	316	457	807	413	**957**
10000	324	473	841	426	**1093**
20000	330	477	784	438	**1199**

Table 5.3 - Distance from rupture to a maximum concentration of 100ppm H_2S from a release of a 30% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)** D2	D5	D10	E3	F2
500	1385	**1998**	1960	1709	1446
1000	1708	**2646**	2523	2179	2185
2500	1996	**3671**	3330	2610	3130
5000	2127	**4359**	3824	2807	3610
10000	2234	**4832**	4190	2973	3910
20000	2309	**5127**	4458	3082	4178

For the releases of 2.5% H_2S gas from the shorter segment lengths (500m and 1000m) a maximum hazard distance is related to the meteorological condition of D10 (neutral stability, wind speed of 10m/s). For releases of 2.5% H_2S gas from the longer segment lengths (2.5km to 20km) a maximum hazard distance is achieved with the meteorological condition of F2 (stable conditions, wind speed of 2 m/s). For releases of 30% H_2S gas from all segment lengths a maximum hazard distance to a concentration endpoint of 100ppm H_2S occurs in the meteorological condition of D5 (neutral stability, wind speed of 5m/s).

5.3 Dosage Endpoint

The dosage endpoint is the maximum distance from the rupture site where the toxic load profile is equivalent to 100ppm H_2S for a period of 30 minutes. Table 5.4 shows the maximum distances to an equivalent concentration of 100ppm H_2S for 30 minutes from a 2.5% H_2S gas release under differing meteorological conditions. Table 5.5 shows maximum distances to an equivalent concentration of 100ppm H_2S for 30 minutes from a 30% H_2S gas release under different meteorological conditions. The maximum distance to the equivalent concentration of 100ppm H_2S for 30 minutes for each segment length over all the conditions evaluated is indicated in bold.

Table 5.4 - Distance from rupture to a maximum equivalent concentration of 100ppm H_2S for 30 minutes from a release of a 2.5% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)**				
	D2	**D5**	**D10**	**E3**	**F2**
500	130	162	**174**	143	135
1000	180	224	**246**	207	218
2500	218	287	345	265	**355**
5000	230	309	399	288	**460**
10000	241	324	449	299	**526**
20000	279	384	545	351	**604**

Table 5.5 - Distance from rupture to a maximum equivalent concentration of 100ppm H_2S for 30 minutes from a release of a 30% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)**				
	D2	**D5**	**D10**	**E3**	**F2**
500	771	**926**	854	902	851
1000	1110	1320	1152	1343	**1346**
2500	1521	2009	1607	1924	**2230**
5000	1712	2604	1905	2241	**2821**
10000	1855	3076	2202	2421	**3195**
20000	1926	**3524**	2363	2540	3455

For the releases of 2.5% H_2S gas from the shorter segment lengths (500m and 1000m) a maximum hazard distance is related to the meteorological condition of D10 (neutral stability, wind speed of 10m/s). For releases of 2.5% H_2S gas from the longer segment lengths (2.5km to 20km) a maximum hazard distance is achieved with the meteorological condition of F2 (stable conditions, wind speed of 2 m/s). For releases of 30% H_2S gas from the shortest (500m) and longest segments (20km) modelled, a maximum hazard distance to a dosage endpoint equivalent to a concentration of 100ppm H_2S for 30 minutes occurs in the meteorological condition of D5 (neutral stability, wind speed of 5m/s). For the intermediate segment lengths (1km to 10km) the maximum hazard distance occurs in the meteorological condition F2 (stable conditions, wind speed of 2m/s). Section 5.5 provides a discussion of the effect of the meteorological condition on the maximum hazard extent.

5.4 *Lethality Endpoint*

The lethality endpoint is the maximum distance from the rupture site to a location where the dose is equivalent to that which could cause lethality in a maximum of 1% of the exposed population using the TSR probit equation. Table 5.6 shows the maximum distances to the 1% probability of lethality from a 2.5% H_2S gas release under different meteorological conditions. Table 5.7 shows maximum distances to the 1% probability of lethality from a 30% H_2S gas release under different meteorological conditions. The maximum distance to the lethality location for each segment length over all of the meteorological conditions evaluated is indicated in bold.

Table 5.6 - Distance from rupture to a maximum 1% probability of lethality from a release of a 2.5% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)**				
	D2	**D5**	**D10**	**E3**	**F2**
500	82	98	**107**	86	81
1000	126	154	**159**	138	129
2500	176	218	**229**	204	**229**
5000	195	248	276	234	**307**
10000	209	268	320	252	**363**
20000	254	335	**390**	309	385

Table 5.7 - Distance from rupture to a maximum 1% probability of lethality from a release of a 30% H_2S gas

Segment Length (m) (proportional to volume of gas released)	**Hazard Distance for Specified Meteorological Conditions (m)**				
	D2	**D5**	**D10**	**E3**	**F2**
500	524	**641**	620	602	568
1000	799	932	835	**935**	896
2500	1221	1410	1151	1504	**1599**
5000	1457	1821	1380	1866	**2209**
10000	1604	2180	1551	2060	**2612**
20000	1701	2462	1687	2215	**2879**

For the releases of 2.5% H_2S gas from the shortest (500m to 2.5km) and longest (20km) segment lengths a maximum hazard distance is related to the meteorological condition of D10 (neutral stability, wind speed of 10m/s). For releases of 2.5% H_2S gas from the 2.5km segment length a maximum hazard distance is achieved with both the meteorological condition of D10 (neutral stability, wind speed of 10 m/s) and with the meteorological condition of F2 (stable conditions, wind speed of 2m/s). For releases of 2.5% H_2S gas from the longer (2.5km to 10km) segment lengths a maximum hazard distance is achieved with the meteorological condition of F2 (stable conditions, wind speed of 2 m/s).

For the releases of 30% H_2S gas from the shortest segment length (500m) a maximum hazard distance is related to the meteorological condition of D5 (neutral stability, wind speed of 5m/s). For releases of 30% H_2S gas from the 1km segment length a maximum hazard distance is achieved with the meteorological condition of E3 (stable conditions, wind speed of 3 m/s). For releases of 30% H_2S gas from the longer (2.5km to 20km) segment lengths a maximum hazard distance is achieved with the meteorological condition of F2 (stable conditions, wind speed of 2 m/s).

5.5 Interpretation of Results

The meteorological condition F2 has been identified (AEUB, 2002) as the condition liable to produce the greatest hazard distances by virtue of the minimal dispersion and dilution of the plume that occurs at the low wind speed in the stable conditions. In almost half (17/36) of the cases developed for this study, the meteorological condition F2 did not have the maximum hazard distance. One quarter (9/36) of the maximum distances occurred during condition D5, one fifth (7/36) of the maximum distances occurred during condition D10, and 3% (1/36) of the maximum distances occurred during condition E3. The reason for the meteorological condition F2 not always corresponding with the maximum hazard distance relates to the plume dispersion characteristics. In some cases more buoyant plumes (those gases with a H_2S content of <35% are generally buoyant once the gas plume has expanded to its maximum extent at atmospheric pressure and temperature at expanded atmospheric conditions (Dowsett, 2003)) have a greater vertical component (lift off) than the Gaussian component of SLAB model allows and there is vertical sheer of the plume. Because there is conservation of mass within the plume the vertical sheer causes the linear distance of the plume to be overestimated in those cases. For hazard modelling the greatest hazard distance under any meteorological condition is used regardless of whether or not it corresponds to a meteorological condition of F2. If the initial trajectory of the plume is vertical then the plume has lower hazard distances. For screening level purposes the initial trajectory is assumed to be horizontal, and a more cautious hazard distance estimate is the result.

In hazard analyses the range of meteorological conditions should be reviewed to see which case results in the greatest hazard distance. In order to accurately represent the range of meteorological conditions in a risk assessment, all of the cases should be evaluated and a probability of the condition's occurrence should be applied to each case and all cases can then be included in the risk calculation. The EUB is now considering the inclusion of conditions F2, E3 and E5 in their hazard and risk assessment protocol (Neilson, 2002).

Table 5.8 provides a summary table of the results obtained from the maximum distances to the hazard conditions.

Table 5.8 - Maximum distances to Hazard Conditions

% H_2S	Segment Length (m) (proportional to volume of gas released)	Maximum distance in meters to Concentration 100ppm	 Dosage 100ppm for 30 min	 Lethality 1%
2.5	500	543	174	107
	1000	652	246	159
	2500	813	355	229
	5000	957	460	307
	10000	1090	526	363
	20000	1200	604	390
30	500	2000	926	641
	1000	2650	1350	935
	2500	3670	2230	1600
	5000	4360	2820	2200
	10000	4830	3200	2610
	20000	5130	3520	2880

*Distance values in table have been rounded to 3 significant digits (confidence in the precision of these estimates is likely lower).

The maximum distances presented for each of the concentrations and corresponding segment lengths illustrates the distances to the different endpoints. The concentration endpoint is the most stringent endpoint for the industry to accommodate because it is located at the greatest distance from the pipeline creating the largest potential emergency response planning zone. The lethality endpoint is located in closest proximity to the source and thus is the least stringent. The dosage endpoint of 100ppm for 30 minutes which corresponds to a toxic load (calculated through the TSR equation) of 3.0x10^{6} ppm$^{2.5}$min is more stringent than the lethality endpoint of 13.6x10^{6} ppm$^{2.5}$min and thus corresponds to a greater hazard distance. The most stringent condition, the concentration endpoint, correlates with the greatest hazard distance in all of the cases reviewed in this study. It has been identified by RWDI that for some releases of longer duration and high concentration the dosage endpoint will be the most stringent hazard criterion (RWDI, 2000).

Segment volumes for each length of pipe at each of the two studied concentrations were calculated using a spreadsheet developed by RWDI for use by the EUB. This spreadsheet uses compressibility factors and the Peng-Robinson equation of state to calculate the volume of the pipe segment under the conditions entered into the spreadsheet and to assign an EUB level to the release (1-4) (Dowsett, 2002). The Peng-Robinson is an equation of state based on the ideal gas law, which uses critical and reduced parameters. The critical and reduced parameters were discussed in Section 3.0. The details of the Peng-Robinson equation of state are included as Appendix 1.

The EUB hazard levels are presented as Table 3.1. The EUB have generated a nomograph from which the hazard distance corresponding to a release volume can be identified (AEUB, 2001). The calculation is based on release rate, volume and concentration. The rationale behind the hazard distance is identified in the CPA Guidelines for Preparation of Sour Gas Emergency Response Plans (CPA, 1987).

The pipe volume calculation does not account for the extra volume that seeps into the pipeline during a rupture prior to the ESD valves being triggered (often at 70% of normal operating pressure) (Dowsett, 2002). In order to represent more accurately the volume of gas released during a pipeline rupture, appropriate extra volume factors were obtained from the proprietary transient mass flow input files generated by RWDI for the SLAB runs. From the data available, the missing data points were graphically extrapolated. Table 5.9 gives the extra volume factors for the two concentrations studied in a pipe with an inner diameter of 202.7mm, at an operating pressure of 10000kPa and a temperature of 5°C. The extrapolated values are italicized.

Table 5.9 - Extra volume factors (RWDI, 2002)

Segment Length (m)	**Extra volume factor - 2.5% H_2S**	**Extra volume factor - 30% H_2S**
500	2.193	1.894
1000	1.476	1.326
2500	*1.125**	1.065
5000	*1.035**	*1.010**
10000	*1.009**	*1.003**
20000	1.000	1.000

* extrapolated value

Table 5.10 contains the segment lengths, the segment volume (modified from the RWDI - EUB spreadsheet to account for the extra volume factor) and the H_2S volume released.

Table 5.10 - Volumes of Gas available for release from Pipe Segments

% H_2S	Segment Length (m)	Total Release Volume (m^3)	H_2S Release Volume (m^3)
2.5	500	5700	140
	1000	7670	190
	2500	14500	360
	5000	26800	670
	10000	52100	1300
	20000	103000	2590
30	500	8520	2540
	1000	11800	3550
	2500	23800	7140
	5000	45100	13500
	10000	89600	26900
	20000	179000	53600

* Values in the table have been rounded to 3 significant figures

Table 5.11 contains the H_2S pipe volume as identified in the spreadsheet, the modified H_2S release volume, the EUB hazard distance and the associated level. The EUB hazard levels were presented as Table 3.2 and the hazard distance is calculated using the nomographs detailed in AEUB ID 2001-5 (AEUB, 2001) which are based on calculations that are included in AEUB ID 97-6 (AEUB, 1997).

Table 5.11 - Gas Release Volumes and EUB Hazard Distances and Levels

% H_2S	Segment Length (m)	H_2S pipe volume (m^3)	H_2S release volume (m^3)	AEUB hazard level	AEUB Hazard Distance (m)
2.5	500	65	140	1	230
	1000	130	190	1	440
	2500	320	360	2	970
	5000	650	670	2	1700
	10000	1300	1300	2	2700
	20000	2600	2590	3	4000
30	500	1330	2540	3	2800
	1000	2700	3550	3	4100
	2500	6700	7140	4	6500
	5000	13400	13500	4	9400
	10000	26800	26900	4	14600
	20000	53600	53600	4	25100

* Values in the table have been rounded to 3 significant figures

Graphical representations of the released volume of H_2S gas plotted against the maximum hazard distances are provided in Figure 5.2 for the 2.5% H_2S gas scenarios and Figure 5.3 for the 30% H_2S gas scenarios.

Figure 5.2 - Maximum Distance to Hazard (2.5% H2S)

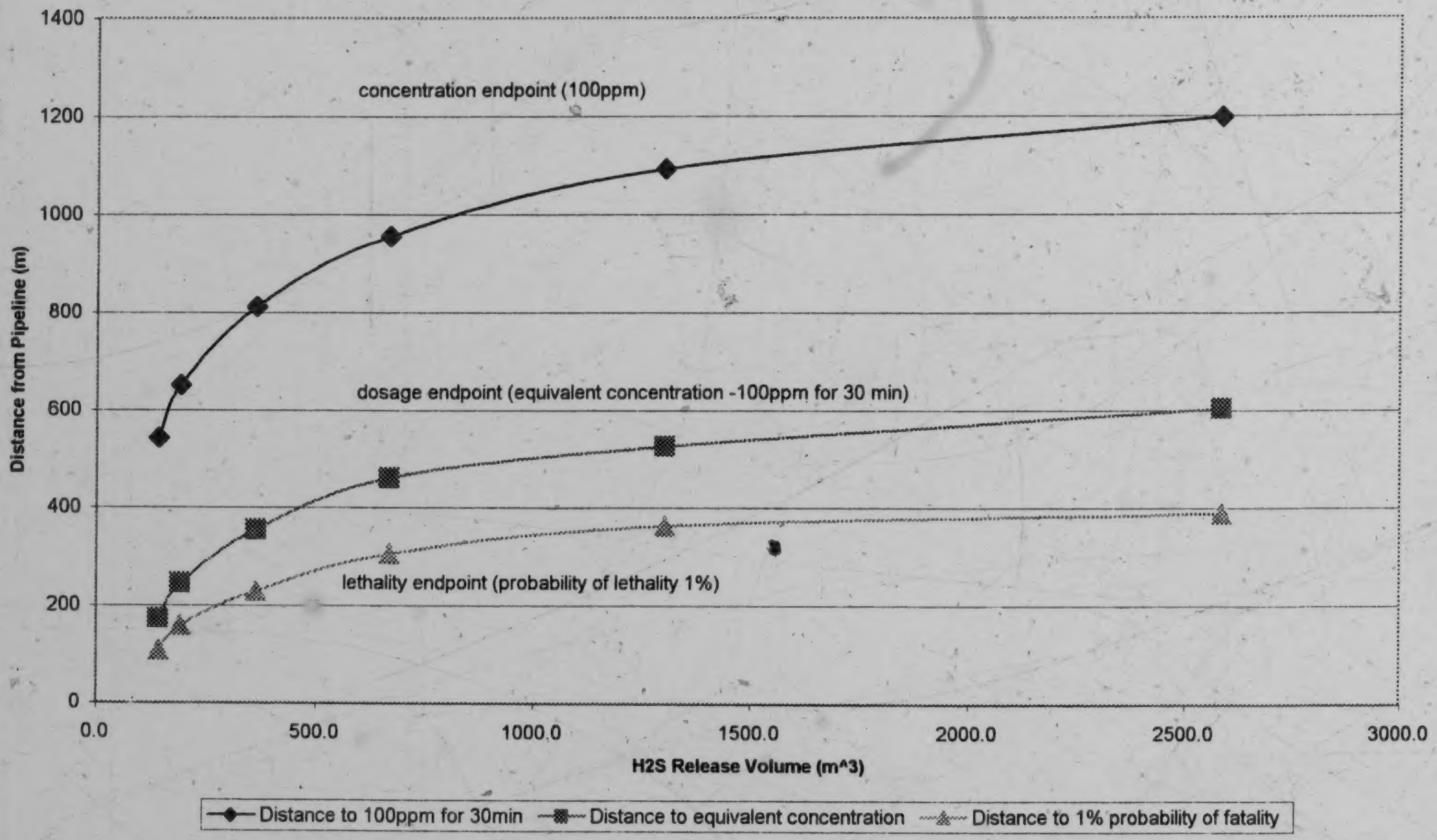


Figure 5.3 - Maximum Distance to Hazard (30% H2S)

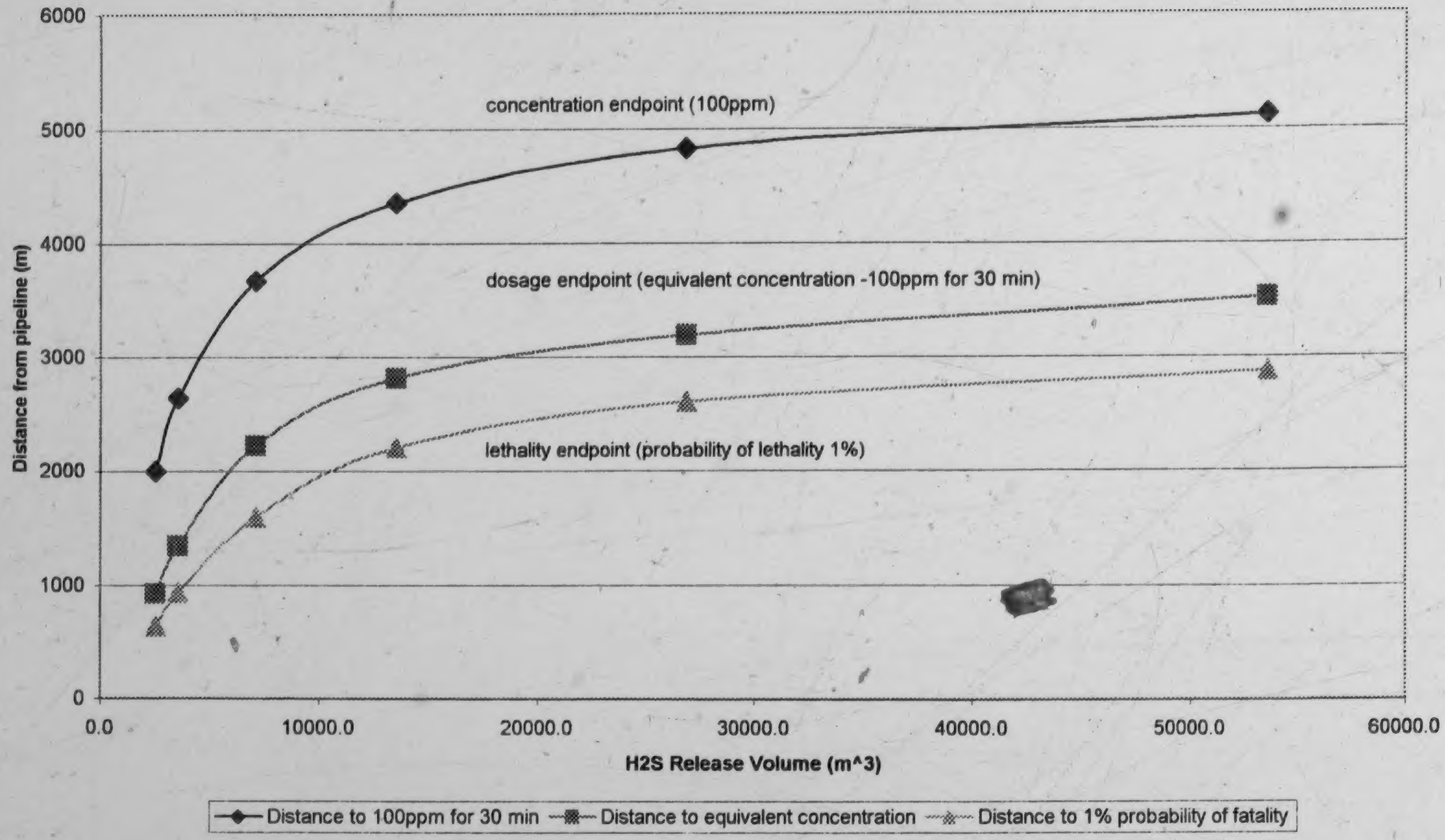


Figure 5.4 is a combined plot of the two data sets showing the three curves (concentration, equivalent concentration and 1% probability of lethality) for each of the two scenarios modelled (2.5% H_2S and 30% H_2S). There is a discontinuity in the curves because the data are generated from two distinct pipeline scenarios.

The data set for the 2.5% H_2S scenario are located closer to the origin with release volumes up to 2600m^3 and the data set for the 30% H_2S scenario illustrate situations covering release volumes up to 60,000m^3. Figure 5.5 presents the combined data sets showing continuous lines bounding the discontinuity and representing a maximum distance to be considered (i.e. all of the considered data points lay on or below the line).

Figures 5.6 and 5.7 are plots of the combined data for the distance to the concentration endpoint (100ppm on 30 minute meteorological averaging) and the EUB hazard distance (which is based on a concentration endpoint of 100ppm on 3 minute meteorological averaging) for both data sets (2.5% H_2S and 30% H_2S). Figure 5.6 shows the data for the 2.5% H_2S cases, Figure 5.7 shows the data for the 30% H_2S cases, and Figure 5.8 is a plot showing data for both the 2.5% H_2S and 30% H_2S cases, again with a discontinuity. In Figure 5.6 a crossover in the curves is evident in the event of a pipeline rupture where the H_2S gas release volume is less than 275m^3. For all of the data points on the 30% H_2S curves the EUB hazard distance is in excess of the concentration endpoint distance. For the 2.5% H_2S curve where there are low H_2S gas release volumes, (at distances from the pipeline less than 750m) the EUB hazard distance is not less than the 100ppm (on 30 minute averaging) concentration endpoint.

Figure 5.4 - Distances to Hazard Endpoints

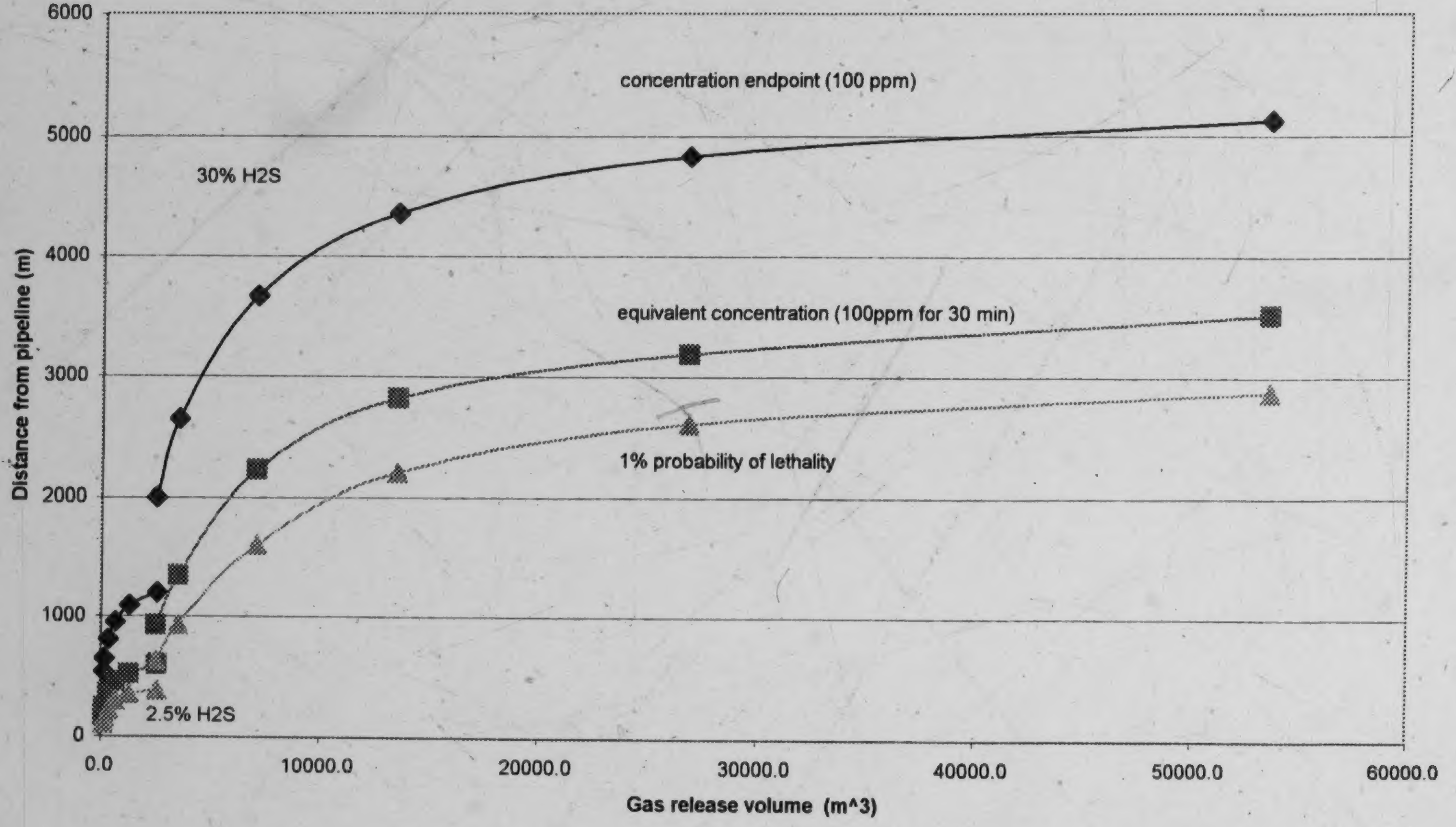


Figure 5.5 - Combined Plot with data from 2.5% and 30% H2S releases

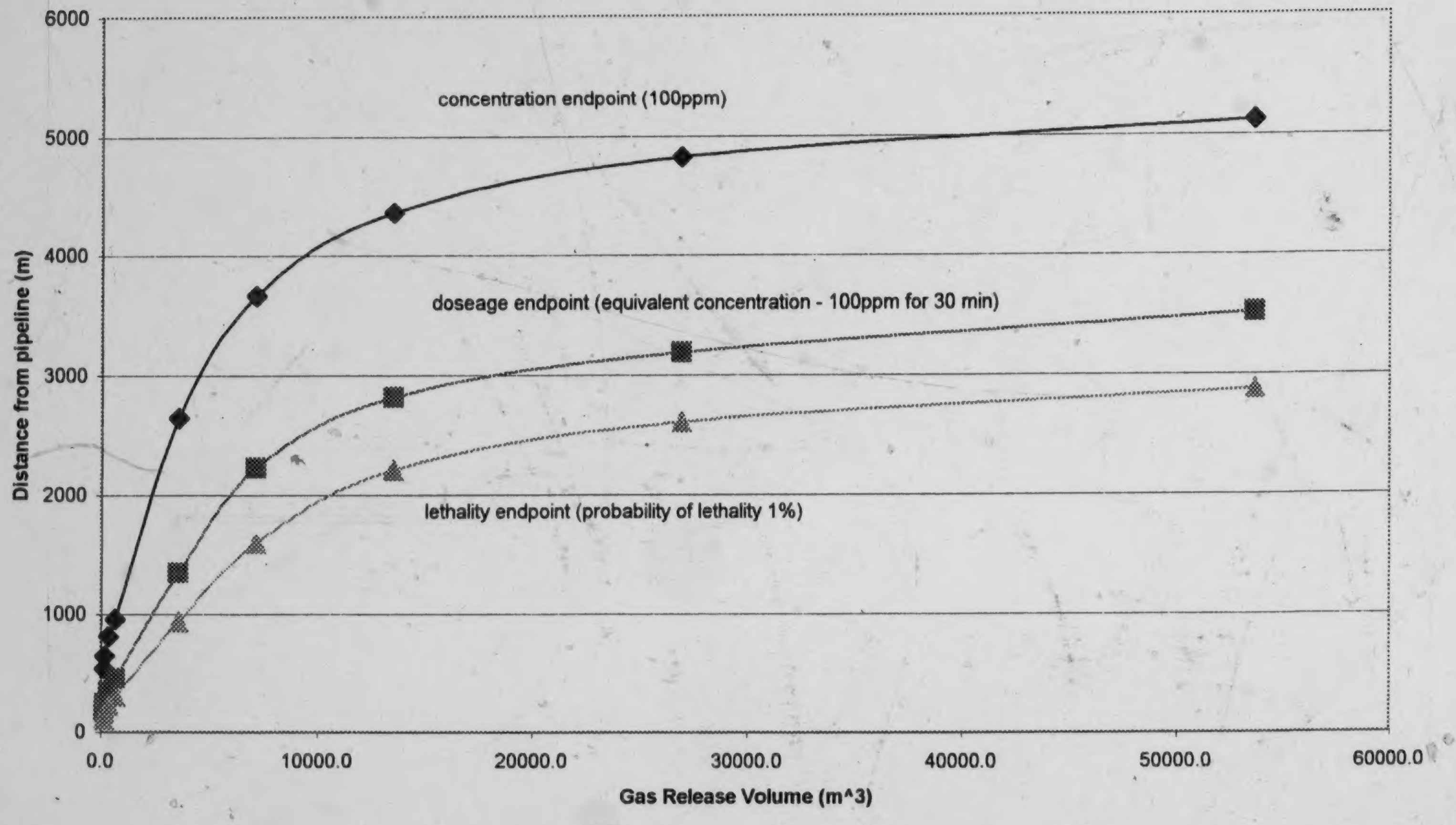


Figure 5.6 - Concentration Endpoint (100ppm) and the EUB Hazard Distance (2.5% H2S)

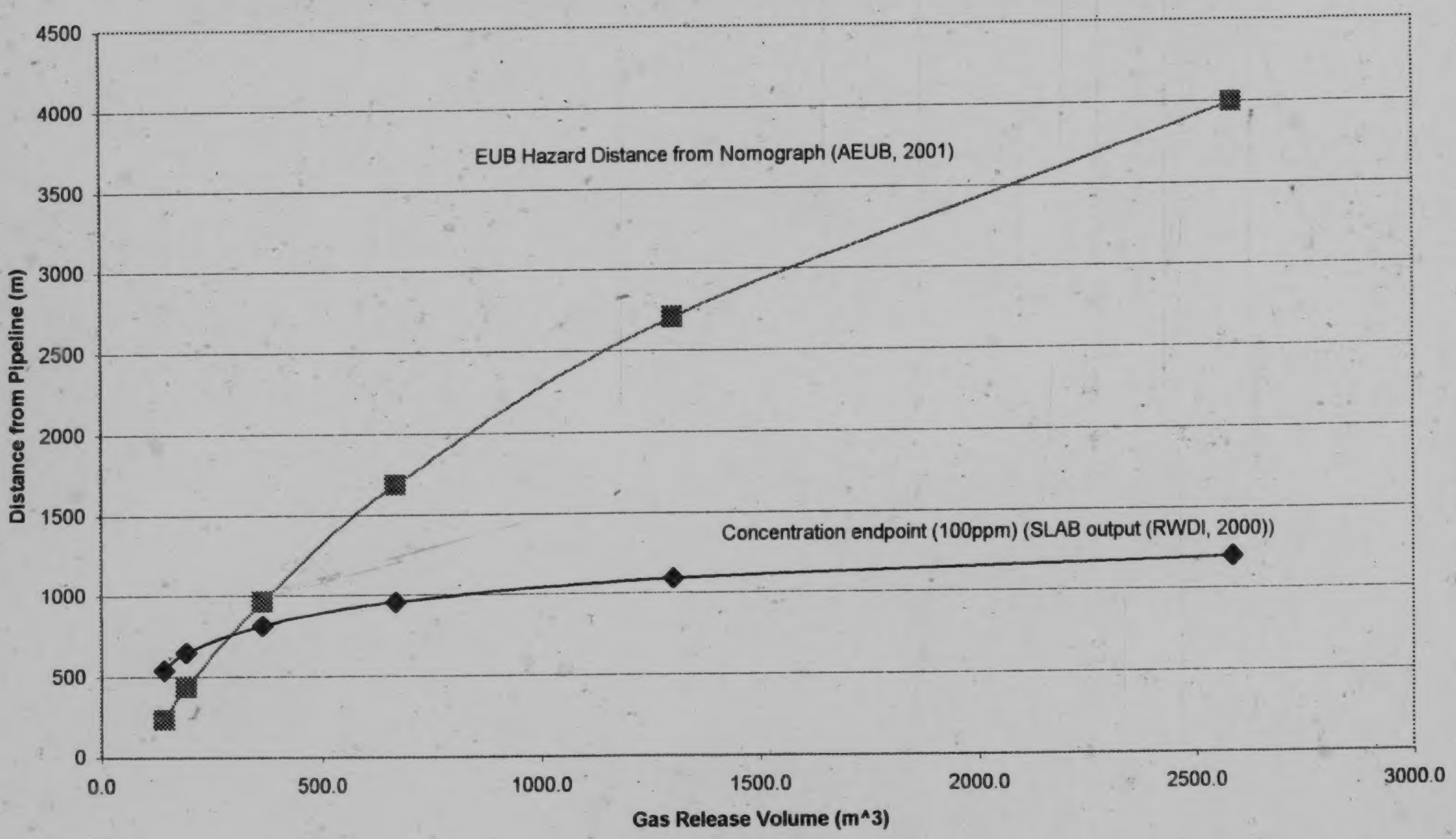


Figure 5.7 - Concentration Endpoint (100ppm) and the EUB Hazard Distance (30% H2S)

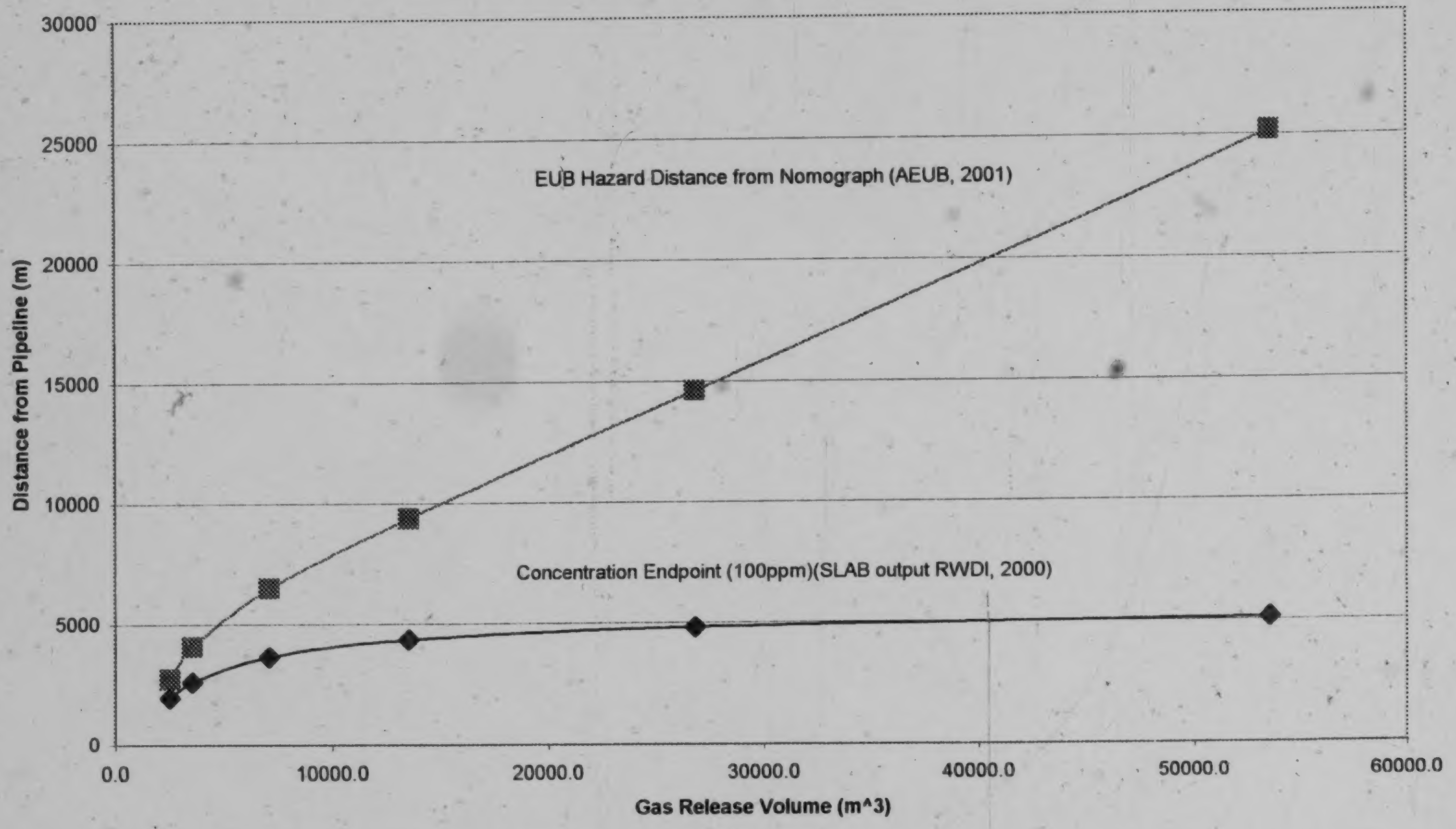


Figure 5.8 - Distance to Concentration Endpoint (100ppm) and EUB Hazard Distance

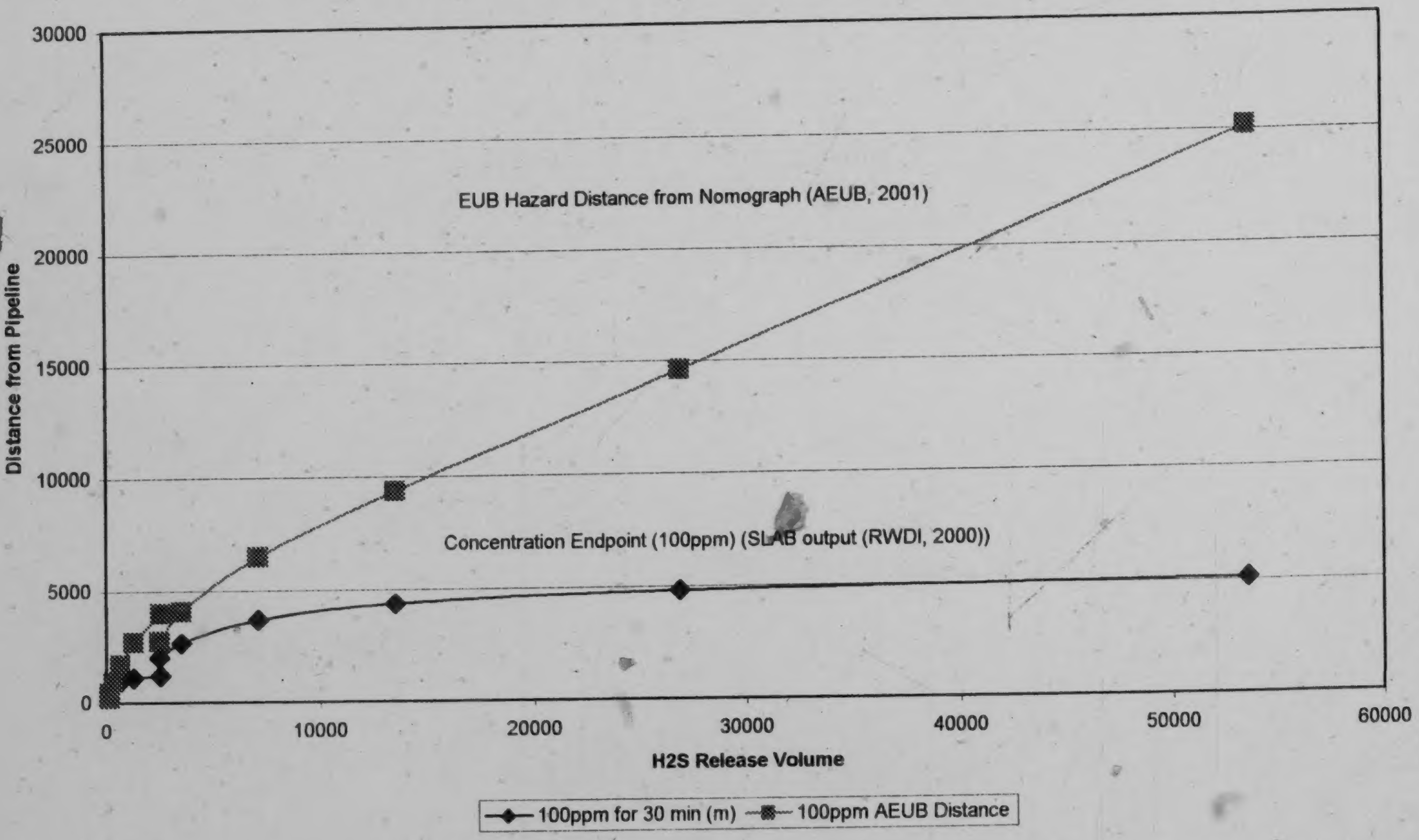


Figure 5.8 is the combined plot for both the 2.5% and the 30% H_2S cases. (The EUB endpoint is generated from a nomograph derived from an equation based on the CPA directive regarding sour pipelines and facilities (CPA, 1987, AEUB 2001)). The discontinuity on the graph is again due to the two distinct data sets and has been eliminated in Figure 5.5 by selecting the point from each of the data sets which lay closest to the line drawn through the combined data sets. No points lay above the line, thus the combined data set without discontinuity can be considered to present a cautious "best estimate distance" based on volume of gas released.

Figures 5.2 and 5.3 illustrate that the criterion that pose a greater expected risk occur closer to the pipeline. The isopleth for 1% lethality (based on the Triple Shifted Rijnmond equation) is located much closer to the pipeline in distance than the concentration endpoint of 100ppm; this is because a 1% lethality response requires more than a peak at 100ppm, it requires a sustained high level concentration-time exposure in keeping with the TSR. Figure 5.4 is a combined plot of the release volumes plotted against the hazard distances. This graph shows that the released volume of H_2S cannot be considered in isolation, rather the H_2S concentration and the duration of the release period must be considered in conjunction with the release volume. Figures 5.6, 5.7 and 5.8 show the difference between the modelled data points and those generated using the EUB nomograph. The 100ppm curve as generated through the use of SLAB output data lies below the line generated through the use of the EUB nomograph in all circumstances except the low volume release shown in Figure 5.6. The EUB nomograph is used to define the EPZ for releases from individual sour wells and facilities based on the volume of

H_2S released (AEUB, 2001). These curves illustrate that the nomograph is extremely cautious in the hazard distance generated. This difference indicates the need for review of the data analysis tools currently utilized by the EUB for determination of hazard distances. (This review is currently ongoing (Provincial Advisory Committee on Public Safety and Sour Gas, 2000).) The EUB nomograph curves reflect consideration of release volume of H_2S in isolation rather than in combination with a time element. Where the EUB hazard distance is less than the concentration endpoint distance (100ppm) in the near release area, raises the possibility of underestimating the hazard distance with the nomograph in these specific circumstances and this should be a concern to the EUB.

The idea of calculating the dose as an equivalent exposure (equivalent concentration of 100ppm for 30 minutes) provides a measure by which different types of releases can be compared. A short transient release from a small segment of pipe would have a concentration vs time curve shape similar to that of a sine curve (reaching a peak and then diminishing). A larger release from a longer pipe segment would have a concentration vs time curve that would start at a low value and reach a maximum value where it would plateau before gradually declining when gas dissipated.

The value of the toxic load for the equivalent exposure is $3.0\text{x}10^6\text{ppm}^{2.5}\text{min}$ which is derived from a concentration of 100ppm for 30 minutes. (The value of the toxic load associated with fatalities in 1% of the population according to the TSR is $13.0\text{x}10^6\text{ppm}^{2.5}\text{min}$.) The distance to the point of equivalent exposure load is further from the rupture than the distance associated with a maximum 1% probability of lethality. At the equivalent exposure toxic load ($3.0\times10^{6}ppm^{2.5}min$) it is not expected that there would be fatalities in the population (probit value is negligible (almost zero) which means a very low percentage of the population would be expected to be affected (close to but not equal to zero)). The equivalent exposure toxic load value is very cautious in assuming public safety and presumes a general population, susceptible sub-populations (asthma patients, the elderly, and infants) may have slightly different exposure tolerances.

5.6 Summary Statement - Determination of Exposure Distances

Having completed the specific exposure assessment for the hypothetical pipelines the results will be interpreted to determine specific risk levels both for individual and societal exposures. The risk profile will be completed for the maximum 1% lethality endpoint, because this is the only one of the criteria with a definable adverse consequence.

The difference in hazard distances for differing endpoints illustrates the importance in endpoint selection for public safety management and land-use. The hazard distance used to define the point of emergency evacuation for planning purposes will be different than the setback distance or exclusion zone, reflecting the proximity to the hazard. The emergency evacuation zone is one where if there is a resident population they must be removed from their homes during a release. The setback or exclusion zone is that area around the pipeline where there is no development allowed at all, an area where the hazard level is considered too high to allow the land to be developed for residential or industrial use. For example, in the case of a sour gas pipeline there may be a setback distance of 100m which means that there is no development of any type within 100m of the pipeline and the emergency evacuation planning distance may be 1.6km from the pipeline. This emergency evacuation distance means that during a release individuals residing within 1.6km of the pipeline may be evacuated from their homes during an incident. It is necessary for the emergency plan to be capable of dealing with individuals located within the emergency evacuation planning distance.

6.0 Risk Characterization

The risk of exposure to hydrogen sulphide is characterized for pipelines because of their known failure history. There can only be a risk from a substance or scenario if there is an exposure to the substance or if the scenario occurs. The risk of exposure to sour gas from a ruptured pipeline is an involuntary risk, however it is one that may occur; an analysis, using a Poisson probability distribution for rare events, of historical pipeline failures indicates the probability of future failures, and with failures come the potential for exposure.

In broad or general terms risk is a prediction given:

1) a hazard (a source of danger);
2) an uncertainty of occurrence and outcomes (expressed by probability distributions);
3) adverse consequences (the possible adverse outcomes);
4) a time frame for evaluation; and
5) is justified/classified/vilified by the importance of the risk for the people affected by it. (adapted from Thomas and Hrudey, 1997).

Risk, for the purpose of this assessment, is the product of frequency of events on an annual basis and the potential adverse consequences as applied to a sour gas pipeline (the hazard) (ERCB, 1990). The fifth component of risk - its importance to the people who are affected, has not typically been factored into risk assessment as a numerical term, rather once a value for the risk has been estimated or calculated, risk comparisons are made and risk management or risk mitigation measures are sought.

Risk analysis involves risk identification, risk estimation and risk evaluation. The identification component establishes the existence of a hazard and the determination of the adverse effects associated with it. In the estimation stage the characteristics of the risk are determined by applying available evidence in accordance with current scientific understanding of how nature works (e.g. dispersion models). The determination also considers the magnitude, duration, and intensity of the adverse consequences and the frequency of their components. In the evaluation component of the analysis the significance and acceptability of the probabilities and consequences are rationalized through comparison with natural levels of risk and other unrelated risks (Kates, 1978). The evaluation component involves a consequence valuation where the adverse outcome is identified and the weight of its importance is determined. There is a progression of judgement through the analysis process, but there are bounds placed by science on the range of assumptions that are viable; value judgements do not have such bounds. During the consequence valuation stage, value judgements may, and often do, weigh more heavily than scientific details. The consequence valuation stage is where societal and personal values have an effect on the interpretation of the risk values, and where religious, philosophical and experiential values impact on the importance of the outcome (Angle, 1983).

Zero risk is impossible to achieve in a societal context. This is problematic because it is common that when risk to an individual or small group is considered in isolation, no risk is acceptable. Notwithstanding these difficulties, questions can be asked of science in order to clarify and to explain the adverse outcomes and their potential probabilities (Angle, 1983). While these questions can be asked of science, their answers are considered in conjunction with questions that science cannot answer, regarding the valuation of the consequences and the willingness to accept the risk in return for the societal or personal benefits (Kaplan and Garrick, 1981). For example, in the case of a sour gas pipeline - a fee for lost crop value may initially be paid by the pipeline company for the development of the pipeline on the land, but for the majority of smaller pipelines no additional monies are exchanged over the life of the pipeline. The landowner must weigh the societal benefits of oil and gas production, and transportation to market for consumption for the entire province, against the personal risks of potential exposure to a pipeline leak or rupture. This misalignment between who bears the risk and who shares in the benefit is a common theme underlying risk conflicts.

In this risk assessment for a sour gas pipeline, the hazard being considered is the pipeline integrity failing either through a leak or a rupture. The adverse consequences of the hazard are the public health effects, specifically death associated with exposure to increased concentrations of hydrogen sulphide (H_2S, sour gas). The uncertainty of the outcomes associated with the adverse effects, which are expressed as probability distributions or frequencies are: the frequency of sour gas pipeline failures, the geometry and emission rates associated with the failures, the ambient meteorological conditions and the prevailing wind direction, and the certainty that the pipeline rupture will not be ignited. In order for there to be a risk associated with a specific hazard there must be a potential for exposure (without exposure there is no risk). In the risk assessments performed for the development of sour gas wells and pipelines, the assumption made by the risk assessors is that there is a certainty (a 100% probability) of there being an outdoor receptor (a hypothetical individual) regardless of the time or place of the sour gas release. The risk is assessed as if the receptor is at an outdoor location in the vicinity of the pipeline 24 hours/day, 365 days/year. The assumption of a continuous receptor allows for the comparison of risks on a consistent basis if all risks are assessed for the same receptor population. The assumption of a continuous outdoor receptor inevitably introduces a high degree of caution into the risk equation because there is some, likely much smaller probability, that someone will actually be located at the point of maximum exposure at exactly the time of the failure. Science cannot answer the need for this additional degree of precaution, however scientific methods may be used to poll society to determine the degree of precaution the public wants. The validity of such polling will be challenged by the degree to which the public will understand the issues in question.

6.1 Common risk terms

Risk is described in numerous different terms dependent on both the situation and the risk assessor. In this assessment, risk is assumed to be the annual individual risk of fatality from H_2S exposure resulting from a pipeline failure.

Individual risk describes the annual chance of fatality for an exposed individual; the risk, in this context, is an annual term because the frequency statistic for pipeline failure is an annual term. The calculation assumes that there is a continuous receptor population (if there is a failure there will be an exposed receptor).

Societal risk is a measure of the specific risk to an exposed population from an event (i.e. a sour gas pipeline rupture) and is measured as fatalities/year (ERCB, 1990). The risk is derived from the product of the event frequency (pipeline rupture events/year) and the consequences of the event (fatalities/event). The consequence term, measured in fatalities/event, assumes a uniform population density (population/unit area) and continuously available receptors in order to establish the number of potential fatalities. The population density has a limiting or asymptotic effect on the number of potential fatalities (i.e. when all of the surrounding population have perished no other fatalities will occur, as there are no additional potential receptors available).

Annual risk describes the risk to a specific exposed individual on an annual basis.

Lifetime risk is product of the annual risk and the average life span (the average life span is typically assumed to be 70 years (Thomas and Hrudey, 1997)).

A **maximum 1% probability of lethality** is a location-specific term which means that at a particular distance from the source, with exposure for a time period, the contaminant exposure will be fatal to no more than one percent of the population at that location. The population response is calculated using the Triple Shifted Rijnmond probit equation which incorporates toxic load ($L=C^nt$ where c = concentration, t = time and n = 2.5). The process of creating this shifted equation was intended to assure that this risk estimate would be an upper boundary of what is expected.

A one in a million fatality risk (annual chance of fatality = 1.0×10^{-6}) is interpreted as the risk to the receptor being a probability of one chance in one million of having a fatal exposure to a specific hazard at a specific location in time and space. The risk factors (frequencies and probabilities) for the specific location and time combine to a value of 1.0×10^{-6} when examined. This risk measure can be calculated on either an annual or a lifetime basis depending on the situation. The risk associated with pipeline ruptures is calculated on an annual basis.

Absolute risk is the magnitude of the risk in a group of people who have exposure to the hazard (Gordis, 2000), in this case the people who reside or work directly adjacent to the pipeline and who are at risk of exposure in the event of a pipeline failure. The risks in the unexposed population are included in the calculation as the absolute risk is the exposed risk minus the unexposed risk. The epidemiological measures of risk are all predicted with background rates of disease (or risk) existing. The background rates occur in the "unexposed" are not zero. In order to be at risk a receptor must be exposed.

Relative risk, in epidemiological terms, is the ratio of the rate adverse effects in the exposed population to the rate of adverse effects in the unexposed population (rate = number of adverse effects per unit of population preferably age standardized; RR = exposed risk/unexposed risk) (Gordis, 2000). For a risk assessment involving a pipeline failure the calculation of absolute and relative risk may be less than meaningful as the risk in question occurs only in those with potential exposure, there is no comparison group with which to compare the exposure to this industrial hazard. These terms are more meaningful when the true cause and effect are less certain or for contributory causes rather than complete causes of the effect under consideration (e.g. for certain cancers linked to occupational exposures). In this risk assessment the causality is not in question (sour gas pipeline ruptures and adverse or lethal effects from sufficient exposure to H_2S gas) rather it is the certainty level in the risk values that requires further development.

Years of life lost is a mortality index term which is used to express the greater loss of future life which is associated with the death of a person at a younger age compared to the death of the same person at an older age (Gordis, 2000). Again this measure is not particularly useful as an expression of risk for annual individual fatality associated with a pipeline failure because the nature of the risk is not particularly linked to the age of the exposed population. This form of expressing risk is more useful for comparing different risks affecting different age groups (e.g. motor vehicle fatalities affecting the young vs most cancers affecting the old).

6.2 Risk Estimation

The exposure assessment performed using the SLAB dispersion model allowed for the generation of three endpoints: concentration, dosage (or equivalent concentration) and lethality. Using the lethality endpoint the annual individual risk of fatality from a pipeline rupture was calculated for each of the pipeline cases. The societal risk values from a pipeline rupture for each of the pipeline scenarios over the population densities typical of Alberta were also calculated. The societal risk calculations are presented in Section 6.5.

The values of annual individual risk of fatality for the pipeline rupture cases presented (2.5% H_2S and 30% H_2S over numerous segment lengths) are calculated using failure frequency statistics developed by the EUB (ERCB, 1990). The release geometry and emission rates are stated as constants. The assumptions associated with the constants are included. General industry assumptions (100% probability of non-ignition of the source and 100% probability of an outdoor receptor) are included. The frequency statistics for the meteorological conditions of the area are listed. The frequency statistics were generated from historical weather records from the Environment Canada meteorological station at the Edmonton International Airport which is closest to the site used for this hypothetical risk assessment. The windrose from the Edmonton International Airport for 1992-1997 was used to determine historical frequencies for wind direction and meteorological conditions. Only the low wind speeds (F2 and E3) were utilized to determine the probability of the wind direction for the screening level meteorology used.

An Excel spreadsheet was generated to calculate annual individual risk of fatality profiles for distances away from the rupture using the variables in the risk equation. The two necessary inputs to the spreadsheet were the distance to a maximum probability of lethality of 1% (PD1%) and the plume dispersion angle (plume width angle). The plume was represented as an oval with the distance to the maximum probability of lethality of 1% as the major axis and the intercept of the plume width angle with the vertical or y-axis as the minor axis. The plume was modelled as two-dimensional depicting ground level concentrations, with the assumption of limited vertical dispersion, in order to generate the risk profile. The representation of the plume as an oval initially appears counter-intuitive as a plume from a continuous stack emission appears as a cone; however, as the fixed duration release plume originates very close to ground level a horizontal plane (that is the ground surface) intersects the conical plume yielding the shape of an oval. Figure 6.1 is a schematic which illustrates the oval shape at ground level.

The probability of fatality at the source was assumed to be 100%, the lethality isopleths were then located proportionally along the major axis to the point of probability of lethality of 1% as shown in Figure 6.2b. Lethality isopleths were drawn through the oval plume and each area was then rotated around the origin. Figure 6.2a shows the rotation of the plume segment around the origin. The plume section is bounded by L_1 and L_2 the distances to two different probability of fatality endpoints. The rotated area is in the shape of a donut and has the area $A_T=A_1-A_2$ (where $A_1=\pi L_1$ and $A_2=\pi L_2$). The portion of the donut in which a receptor could be affected is determined by the plume width or dispersion angle (θ) and is calculated as an arc with an area $A_{ARC}=\left(\frac{\theta}{360}\right)*\pi*\left(L_1^2-L_2^2\right)$. The ratio of the area of the plume between the two lethality endpoint distances to the area of the arc is the probability of exposure of a receptor within the plume.

In the simulated data the PD% isopleths were positioned proportionately along the hypothetical plume as illustrated in Figure 6.2b. For example, if the receptor was at the source the PD was assumed to be 100%; if the receptor was at the PD1% distance the PD was assumed to be 1%; at the point in the middle at 50% of the distance the PD% was assumed to be 50%. Actual data generated by RWDI through the use of the program GASCON (which calculates the probability of fatality vs hazard distance for a well release model) were plotted and rather than a straight line as in the (proportionally distributed) simulation the risk curve had a concave shape. Figure 6.3 illustrates the two risk curves. In all cases other than in the vicinity of the source the prorated PD curve lay above the GASCON data points. The area in question is between the 0 and 200m hazard distance with a probability of fatality >0.95 on Figure 6.3. (GASCON data were used as the GASCON program has a toxicological batch file that generates the probability of fatality data as a function of distance along the centre line of the plume, the data were obtained from RWDI for a 30% H_2S well failure.) The prorated PD% was considered to be a cautious upper bound for the risk with the actual points falling on or below the line.

Figure 6.2a illustrates how the plume rotation area was calculated and Figure 6.2b illustrates the proportional positioning of the PD% isopleths. Figure 6.3 is a plot comparing the GASCON generated hazard distance vs the probability of fatality data with the proportionally distributed data generated through the oval plume simulation.

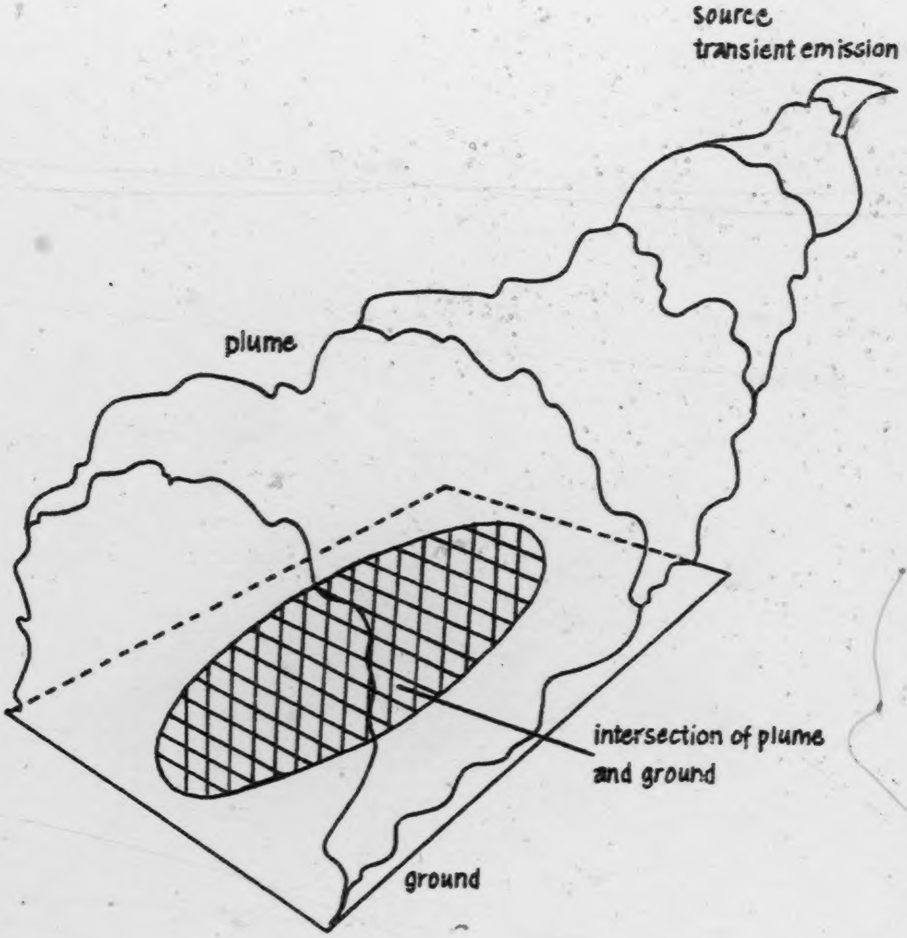

source
transient emission
plume
intersection of plume
and ground
ground

Figure 6.1 - Schematic of Ground Level Oval Plume Shape

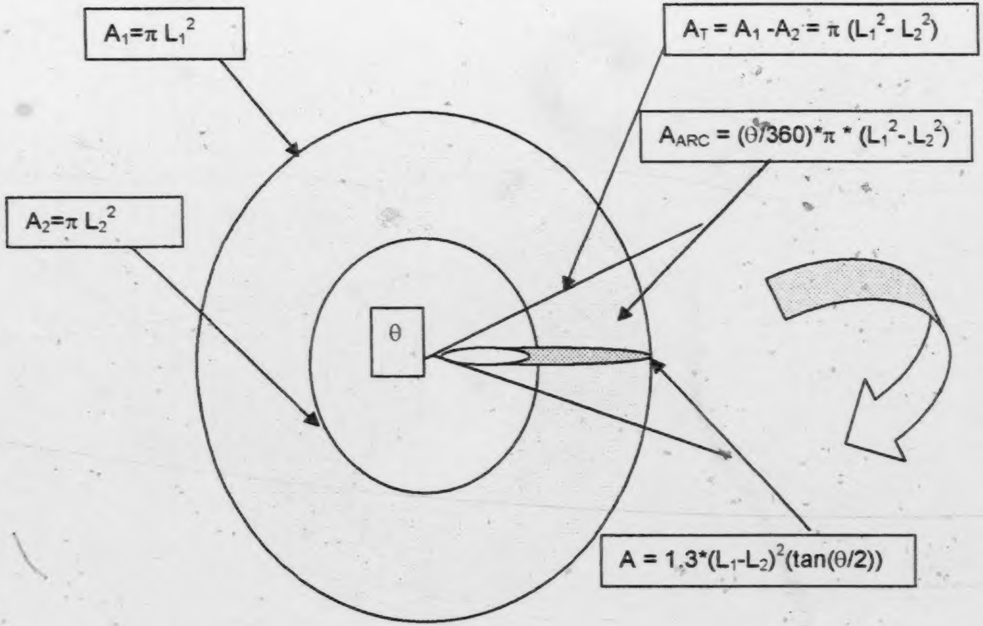

$A_1=\pi L_1^2$
$A_T = A_1 - A_2 = \pi (L_1^2 - L_2^2)$
$A_{ARC} = (\theta/360)*\pi * (L_1^2 - L_2^2)$
$A_2=\pi L_2^2$
θ
$A = 1.3*(L_1-L_2)^2(\tan(\theta/2))$

Figure 6.2a Showing the plume rotation area

Figure 6.2b Showing the probability of fatality as a fraction of the distance from the source

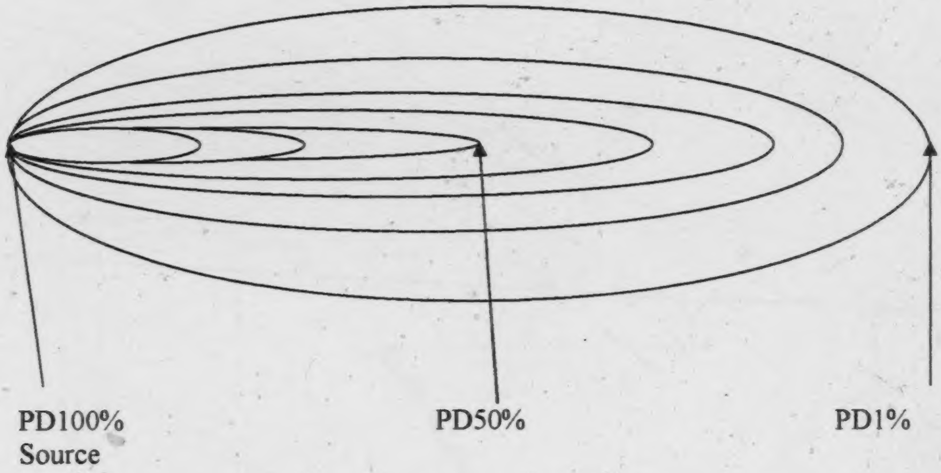
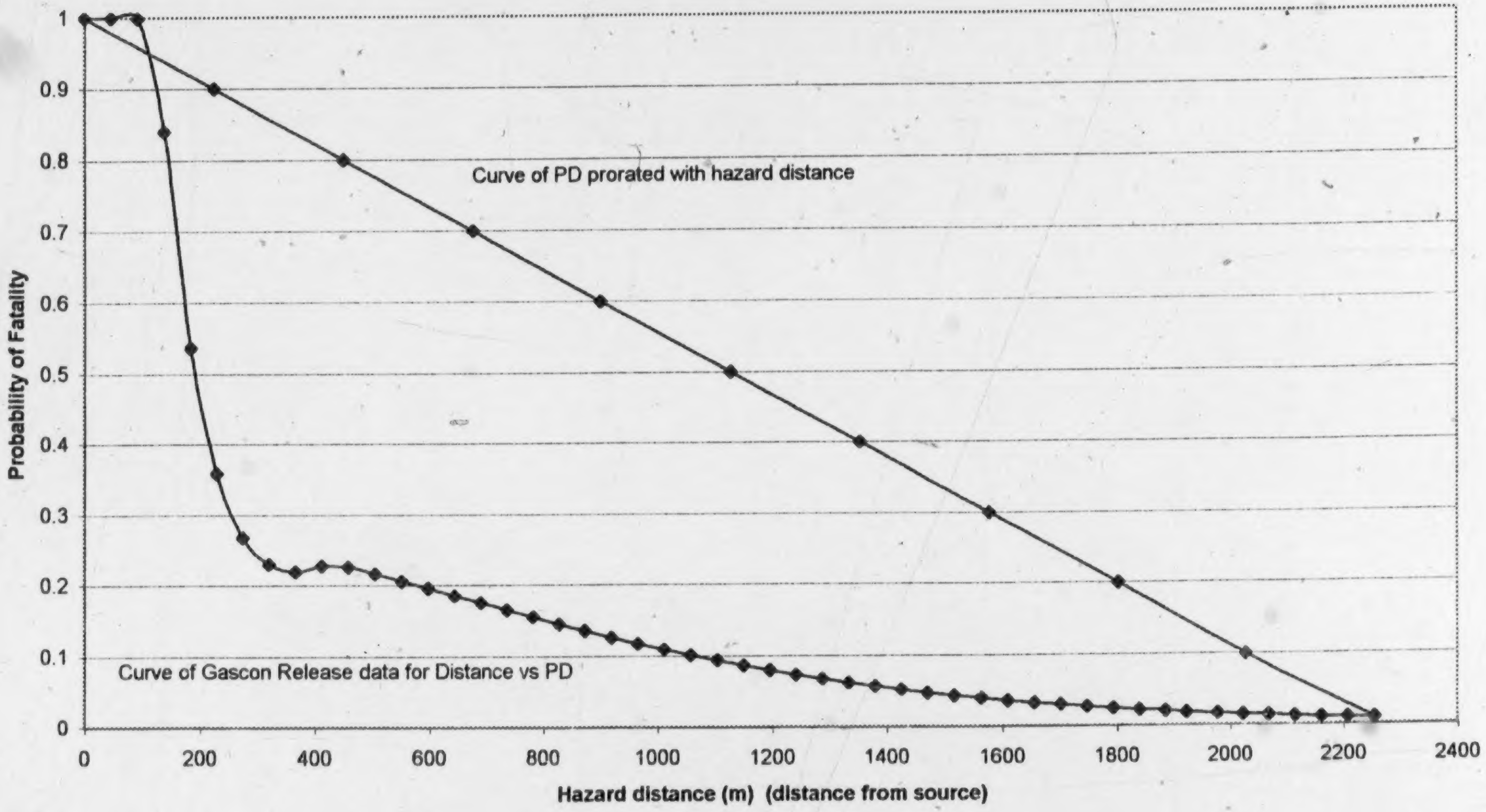

PD100%
Source
PD50%
PD1%

Figure 6.3 - Hazard distance vs Probability of Fatality
30% H2S Well Release



Risk profiles were created for each release event from both the 2.5% and the 30% H_2S pipelines. The risk profile indicates the annual individual risk of fatality at a distance from the source to a point corresponding to the hazard distance of a maximum 1% probability of lethality as generated using the SLAB dispersion model. Comparative points and outcomes are the risk at the maximum 1% probability of lethality and the risk at source (the 100% probability of lethality). As indicated the probability of lethality is calculated using the Triple Shifted Rijnmond probit equation during a meteorological event of F2 or E3 (stable with low wind) classification with the most prevalent wind direction.

Risk curves illustrating specific annual risk of fatality from a specific pipeline (with a set concentration, operating pressure and segment length) are calculated through an integration process where the interaction length stemming from the plume plot is calculated and rotated around the rupture or leak point as shown in Figure 6.3a. The plume is assumed to be symmetrical around the centre line and the ground-level or outdoor receptor contaminant concentration is determined through the integration. These curves allow for the extrapolation of a risk value from a distinct set of pipeline operating conditions for any point in the vicinity of the line. The value of the risk varies depending on the proximity to the rupture and direction of the prevailing wind in relation to the receptor location. These curves are typically presented as individual fatality estimates. The meteorological conditions and wind speeds are not factored into the initial integration; the specific meteorological conditions (the average or expected values) are included in the final values. The level of integration and iteration required to generate the data for the curves is too complex to be completed by hand. A member of the public interested in calculating their specific risk level would be unlikely to be able to wade through all of the assumptions, mathematics and iterations, in order to reproduce a risk value estimated by others.

Societal risk curves show the risk to the surrounding population from a specific failure event. The risk is calculated using population density values and failure frequencies for the facility. Societal risk curves are presented as FN (frequency - number affected) curves which are logarithmic with failure frequency (F) on the y-axis and number of people affected (N) on the x-axis (HSE, 1992). Population densities representative of the Province of Alberta were used for the receptor population data in combination with the existing setback distances. For this risk assessment the societal risk curves were generated by inputting the pipeline characteristics, the hazard distance and the meteorological frequencies into the computer program "PRTLite" created by Shell Global Solutions, the Canadian rights to which are owned by RWDI West.

Three risk values presented herein are:

1) risk profiles for an annual individual risk of fatality for a receptor located at a point in the vicinity of the pipeline;
2) the annual individual risk for a receptor located within the plume (for each of the 2.5% and 30% H_2S cases studied) for a pipeline rupture in the specific location; and
3) the societal risk for the two cases (2.5% and 30% H_2S) studied for a receptor population in the vicinity of the rupture.

6.3 *Annual Individual Risk of Fatality from a Pipeline Rupture*

The annual individual risk of fatality from a pipeline rupture is the annual chance of an individual dying as a result of a specific rupture event. The value is calculated in this assessment through the products of the contributing frequencies and probabilities. The values and sources for the probability and frequency variables in the risk equations are presented in Table 6.1. P(Variable) indicates the probability of the occurrence of the variable.

Table 6.1- Values and Sources of Variables

Variable	Value	Source
Failure frequency	7.45×10^{-4} km/year	Historical EUB records for sour gas pipeline failures 1985-1999
P(non-ignition)	1.0	Pipeline ruptures are not ignited due to their short duration
P(emission rate)	1.0	Probability of emission being a rupture when only ruptures are studied (screening level assumption)
P(release geometry)	1.0	Probability that the rupture will have a horizontal release geometry (screening level assumption)
P(meteorology)	0.21	Percentage of the time for low wind speed and stable atmospheric conditions (data 1992-1996 Edmonton International Airport)
P(wind direction)	0.28	During the lowest wind speeds <3.34m/s the wind was from the W-S quadrant data 1992-1996 Edmonton International Airport
P(outdoor receptor)	1.0	The annual risk of fatality is calculated for a receptor who is outdoors 100% of the time (24 hrs/day, 365 days/year)
P(fatality) case 1	1.0	The receptor was presumed to be located on the pipeline ROW downwind of the source
P(fatality) case 2	0.01	The receptor was presumed to be located at the downwind distance corresponding to a maximum 1% probability of lethality as previously calculated using the TSR probit equation
Interaction length*		Twice the distance to the probability of lethality of 1%.
Plume width angle	15° or 30°	The plume width angle is related to the gas concentration (plume width angle estimates were obtained from experienced modelers at RWDI)

*Explained below

The interaction length of the pipeline is the distance in any direction from the rupture where individuals may be affected by a pipeline release. The interaction length is typically rotated around the pipeline in order to create segments of area with differing risk levels in order to achieve an integrated solution. This was illustrated in Figures 6.3a and 6.3b. Larger release clouds, associated with pipelines containing higher concentrations of product, have longer interaction lengths as more individuals can be affected by a release. A source (rupture) can originate at any point along a pipeline and can be carried by the wind to affect receptors at numerous locations (Concord, 1993). Because there is a defined consequence for the lethality endpoint, twice the hazard distance for the 1% probability of lethality endpoint is used as the interaction length. This is a user-defined term, which by convention has been set using the lethality endpoint. The distance is doubled because the plume could extend along the pipeline in either direction thus the total potential length of pipeline that could be affected by any given leak is twice the PD1% distance.

Dense gases, or gases with a higher H_2S concentration, disperse differently from light gas, or gas with a lower H_2S concentration (this is generally true but not always true). The difference in the plume shape is built into the gas dispersion component of SLAB and is accounted for in the differences in the risk distances. Dense gas releases are less buoyant and produce wider plumes (with more of a pear shape with the base of the pear at the source and the stalk at the end of the plume), while buoyant and neutrally buoyant gas releases have narrower plumes (Dowsett, 2002). The plume width angle used was 15° for the 2.5% stream and 30° for the 30% stream. Streams with low concentrations of H_2S are typically more buoyant and have less dispersion at source accounting for the narrower plume, streams with higher concentrations are denser and have greater dispersion at source producing plumes with a wider base (Dowsett, 2002).

The distance to the lethality endpoint was selected as the basis for the interaction length as it represents a distance at which receptors are affected at a relevant specific level. A maximum probability of 1% (1 chance in 100) is a value that most can relate to. The distance to a maximum probability of lethality of 1% reflects the difference in concentration and volume of gas being released and is greater for greater gas volumes.

Risk is calculated as the product of the frequency of events and the adverse consequences. The frequencies of events are derived from historical statistics: the frequencies of failures and their types and the meteorological conditions and prevailing wind direction. Some of these values are cautiously assumed to have a probability of 1.0 and are assumed to be constant (non-ignition and outdoor receptor). The adverse effect of the hazard is taken as fatality due to sour gas exposure. Two points on the probability distributions were chosen for the risk calculation P=0.01 and P=1.0, that is probability of fatality equaling one chance in a hundred and certain fatality.

The risk curves encompass all of the points in the vicinity of the pipeline and detail their corresponding risk levels; the probability of exposure is calculated from the location from the source but is not assumed to be 100%. The curves do not include the location specific meteorological probabilities; these can be applied to the risk values in order to achieve values that are more location specific. A representative spreadsheet and risk curve are presented in Figure 6.4. All of the curves are provided in Appendix 2.

6.4 Equation derivation and Risk Values

The frequency of events portion of the equation (in units of failures/year) is:

F= (pipeline terms)*(meteorological terms)*constants*interaction length

Where Pipeline terms = (Failure frequency/km*yr)*P(emission rate)*P(release geometry)

Meteorological terms = P(meteorology)*P(wind direction)

Constants = P(non-ignition)*P(outdoor receptor)

Interaction length is in units of kilometers (km).

The consequences or adverse effects of the hazard are:

P(Adverse effects) = P(fatality)*P(exposure)

The probability of fatality is the probability that an individual exposed to that level of contaminant would die; this is calculated using the Triple Shifted Rijnmond probit equation. The probability of exposure is the probability that an individual at distance x from the source would be located within the plume. An individual is presumed to be present and available to be exposed. Figure 6.3a provides that P(exposure) = $\left(\frac{A}{A_{ARC}}\right)$ The probability of exposure is calculated for each individual distance in the risk profile.

The **interaction length** is the distance over which the hazard is applicable; for pipeline ruptures the distance is taken as twice the hazard distance to PD1% in these calculations. (This value must be multiplied into the equation because the failure frequency term is measured in failures/km*year).

Risk in an Oval Plume

Figure 6.4 Representative Risk Spreadsheet and Curve

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 2.879 kilometers

Plume dispersion angle 30 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 30 %

Segment length 20000 m

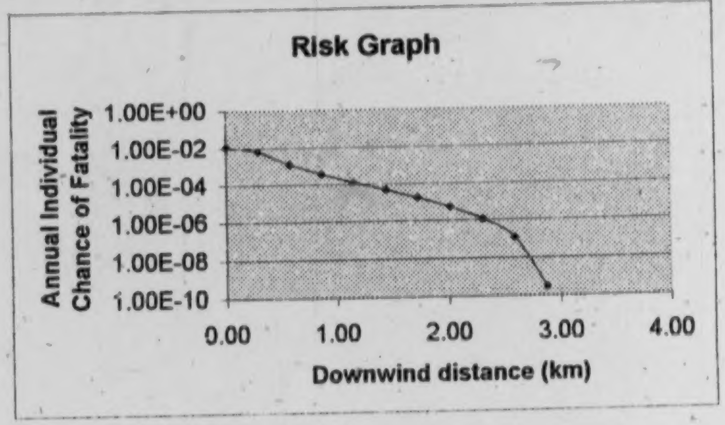
Volume of gas released 53595 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area '(km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.00	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	5.76	1.00000	1.00	0.9983	2.7327	7.45E-04	1.00	1.17E-02
1	0.29	0.10	30.00	1.44E-01	3.86E-02	0.66	1.74E-02	5.73	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	6.66E-03
2	0.58	0.20	30.00	2.88E-01	7.71E-02	1.32	6.98E-02	5.64	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	1.24E-03
3	0.86	0.30	30.00	4.32E-01	1.16E-01	1.99	1.57E-01	5.49	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	3.66E-04
4	1.15	0.40	30.00	5.76E-01	1.54E-01	2.65	2.79E-01	5.28	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	1.32E-04
5	1.44	0.50	30.00	7.20E-01	1.93E-01	3.31	4.38E-01	4.99	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	4.92E-05
6	1.73	0.60	30.00	8.64E-01	2.31E-01	3.97	6.28E-01	4.61	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	1.75E-05
7	2.02	0.70	30.00	1.01E+00	2.70E-01	4.63	8.55E-01	4.11	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	5.36E-06
8	2.30	0.80	30.00	1.15E+00	3.09E-01	5.30	1.12E+00	3.45	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	1.20E-06
9	2.59	0.90	30.00	1.30E+00	3.47E-01	5.96	1.41E+00	2.51	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	1.25E-07
10	2.88	1.00	30.00	1.44E+00	3.86E-01	6.62	1.74E+00	0.81	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	2.97E-10
											2.7327				

Data for Risk Graph

Downwind distance (km)	annual risk of fatality for any individual*
0.01	1.17E-02
0.29	6.66E-03
0.58	1.24E-03
0.86	3.66E-04
1.15	1.32E-04
1.44	4.92E-05
1.73	1.75E-05
2.02	5.36E-06
2.30	1.20E-06
2.59	1.25E-07
2.88	2.97E-10

* assumes that someone will be exposed to the hazardous scenario



Risk=(hazard frequency)*(consequence of the adverse effect) *(interaction length)

For the specific exposure cases presented it is assumed that the individual is located at a distance from the source where the probability of exposure is 100% (i.e. the individual is standing within the plume). The specific meteorological and wind direction probabilities can be applied to the general individual risk values. The individual risk values are presented in Table 6.2. The detailed calculations are provided in Appendix 3.

Table 6.2

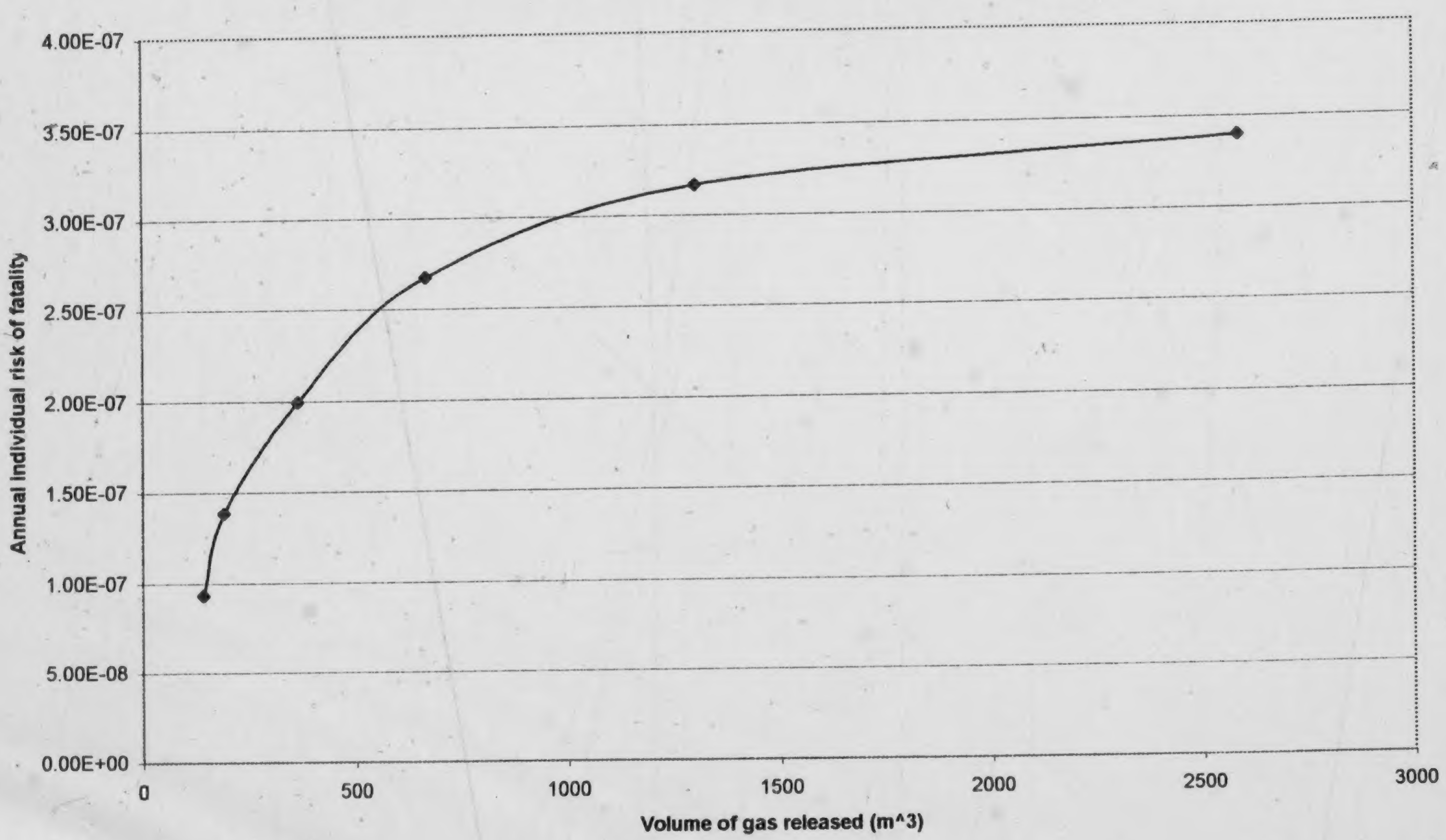
Annual Individual Risk of Fatality from a Pipeline Rupture corresponding to a Maximum Probability of fatality of 1% and a Probability of exposure of 100%

	2.5%H_2S			30% H_2S	
Pipeline Segment Length (m)	H_2S Release volume* (m^3)	Annual Individual Risk of fatality**		H_2S Release volume* (m^3)	Annual individual risk of fatality**
500	140	9.3 x10^{-8}		2540	5.6 x10^{-7}
1000	190	1.4 x10^{-7}		3550	8.2 x10^{-7}
2500	360	2.0 x10^{-7}		7140	1.4 x10^{-6}
5000	670	2.7 x10^{-7}		13500	1.9 x10^{-6}
10000	1300	3.2 x10^{-7}		26900	2.3 x10^{-6}
20000	2590	3.4 x10^{-7}		53600	2.5 x10^{-6}

*Volume values in the table have been rounded to 3 significant figures
**Risk values have been rounded to 2 significant figures.

The individual risk is for any hypothetical individual assuming that someone will be available to be exposed. Figures 6.5 and 6.6 show the curves corresponding to the data in Table 6.2. Figure 6.5 shows only the 2.5% line and Figure 6.6 shows both the 2.5 and 30% lines.

Figure 6.5 - Annual Risk of fatality vs volume of gas released (2.5% H2S line)



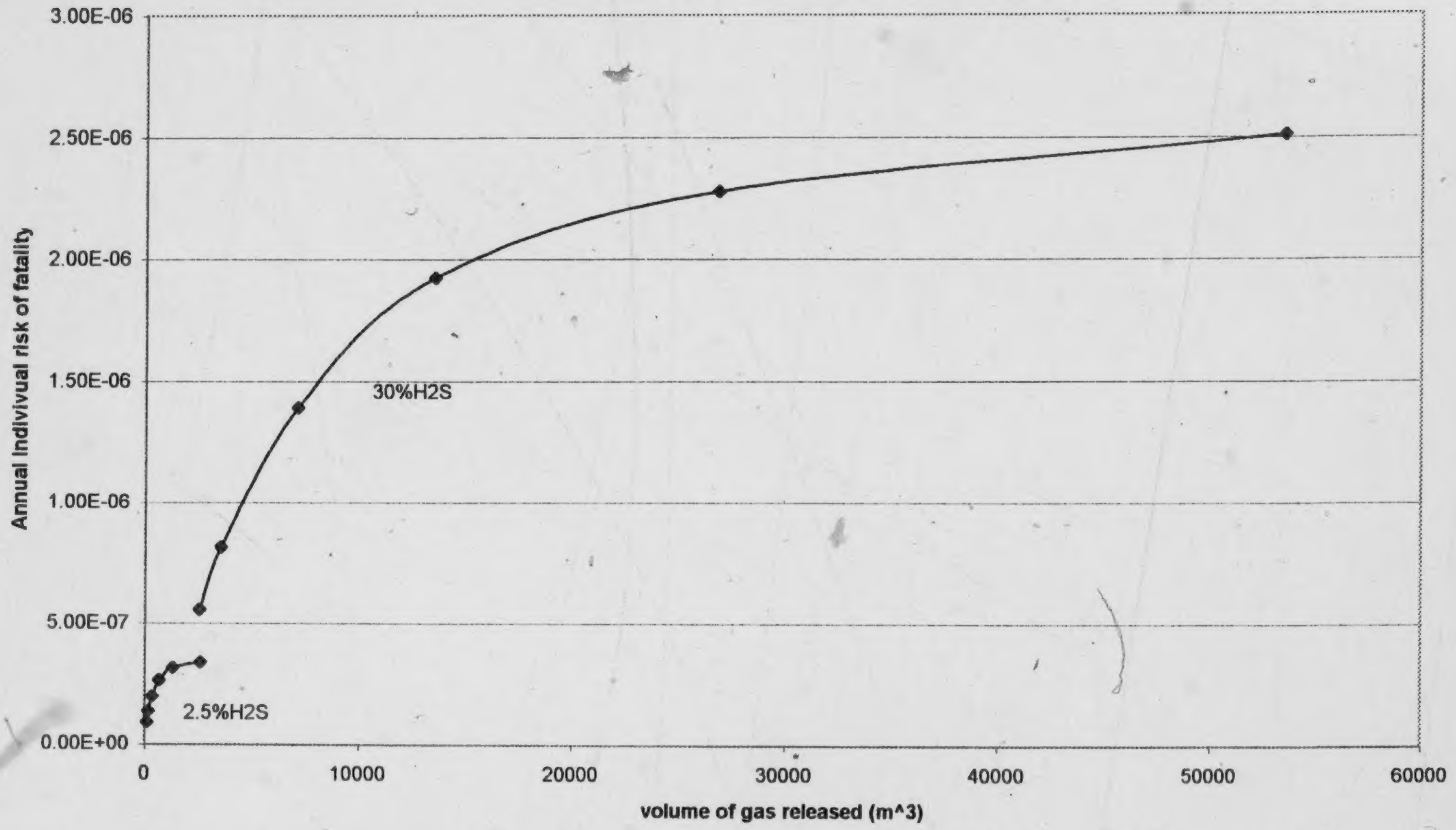


Figure 6.6 - Annual Individual Risk vs Volume of gas released

The difference between the 2.5% H_2S and the 30% H_2S curves is directly attributable to the concentration of the sour gas in the two pipelines studied. Although a similar volume of H_2S gas is released from the 20km segment of 2.5% H_2S line and the 500m segment of 30% H_2S line (2590m^3 vs 2540m^3 see Table 5.11), the time elapsed during the releases means that the distance to the point of 1% probability of lethality is considerably different (390m vs 641m see Table 5.8). For the 2.5% line, the gas is released slowly from a large volume of pipe and over a considerable time period, whereas for the 30% line the gas is released almost instantaneously from a very small pipe volume. Thus the sour gas volume in the plume from the 2.5% line is considerably more dilute and dispersed than the concentrated sour gas in the plume from the 30% line. The annual risk of fatality at the point of the maximum probability of 1% lethality is less for the 2.5% 20km segment (3.40E-07 i.e. 1 chance in 2.9 million) than for the 30% 500m segment (5.58E-07 or 1 chance in 1.8 million). This difference, although both risk estimates are uncertain, can be attributed to the lower risk of fatality associated with a more dilute gas source and the time duration of the releases.

The probability of fatality associated with standing downwind of a pipeline leak while being on the pipeline right-of-way (ROW) is assumed to be 100%. The volume of gas released was plotted against the annual individual risk, calculated using a probability of fatality of 1.0 (100%). These data are presented in Table 6.3. The curves associated with the data in Table 6.3 are shown in Figures 6.7 and 6.8.

Table 6.3 - Annual Individual Risk of Fatality from a Pipeline Rupture at a point on the ROW (100% probability of fatality and exposure)

	2.5%H_2S			30% H_2S	
Pipeline Segment Length (m)	H_2S Release volume (m^3)*	Annual Individual Risk of fatality**		H_2S Release volume (m^3)*	Annual individual risk of fatality**
500	140	9.3×10^{-6}		2540	5.6×10^{-5}
1000	190	1.4×10^{-5}		3550	8.2×10^{-5}
2500	360	2.0×10^{-5}		7140	1.4×10^{-4}
5000	670	2.7×10^{-5}		13500	1.9×10^{-4}
10000	1300	3.2×10^{-5}		26900	2.3×10^{-4}
20000	2590	3.4×10^{-5}		53600	2.5×10^{-4}

*Volume values in the table have been rounded to 3 significant figures
**Risk values have been rounded to 2 significant figures.

It is assumed that the probability of exposure is 100% at the location of the leak. The risk values generated for the hypothetical pipeline risk assessment correspond to the values generated in the more generic risk profile (calculated with the oval plume spreadsheet), except that in the risk assessment the probability of both wind direction and meteorology have been factored into the final risk values. These risk values are clearly much higher, as expected, than the risks at the maximum 1% probability of fatality distances. Effectively, the ROW risk values are reflected in the rationale for having some setback distance. The setback distance makes it much less likely that someone will be located on the ROW at the time of a pipeline failure.

Figure 6.7 - Annual risk of fatality on the ROW vs volume of gas released (2.5% line)

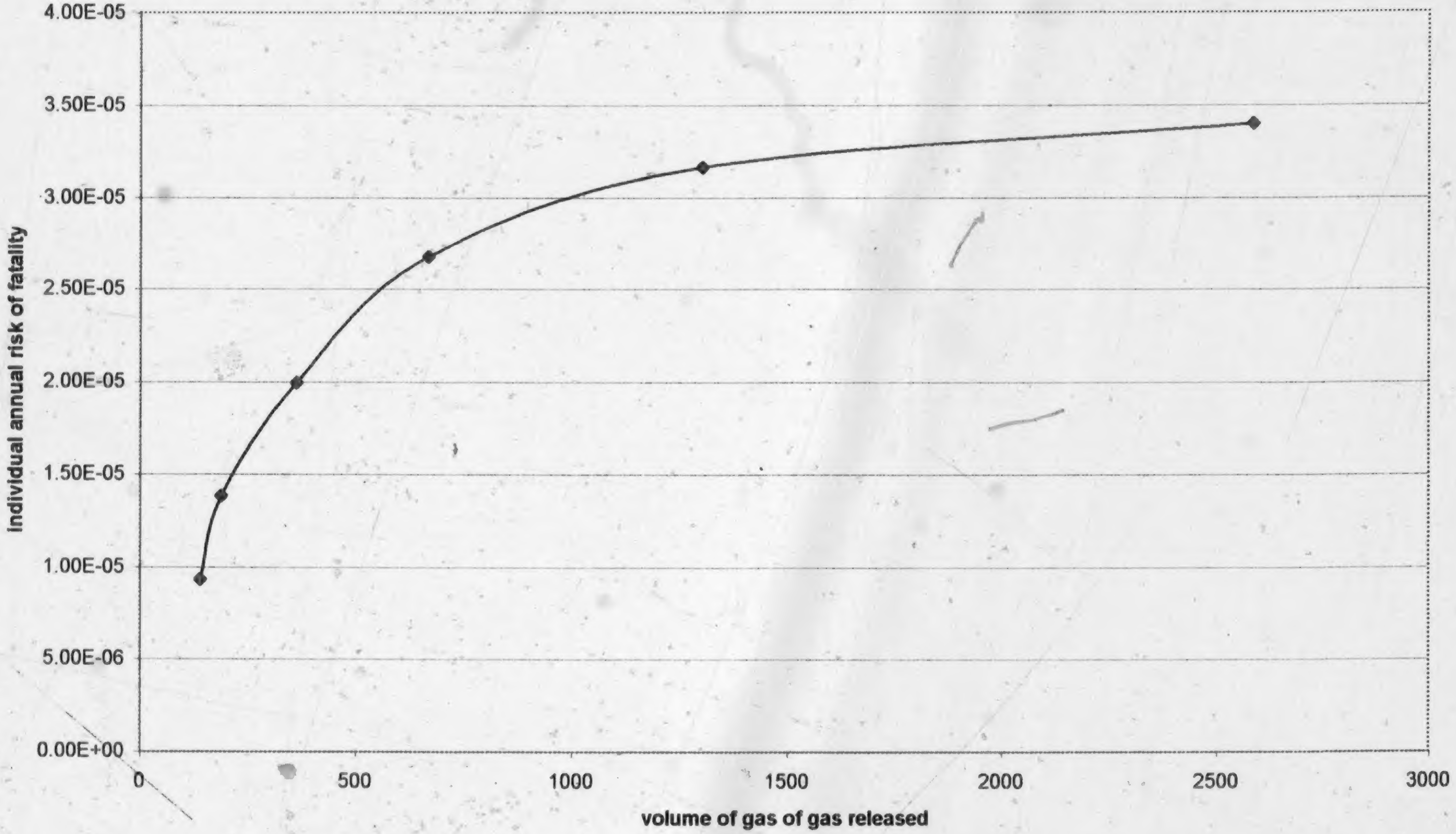
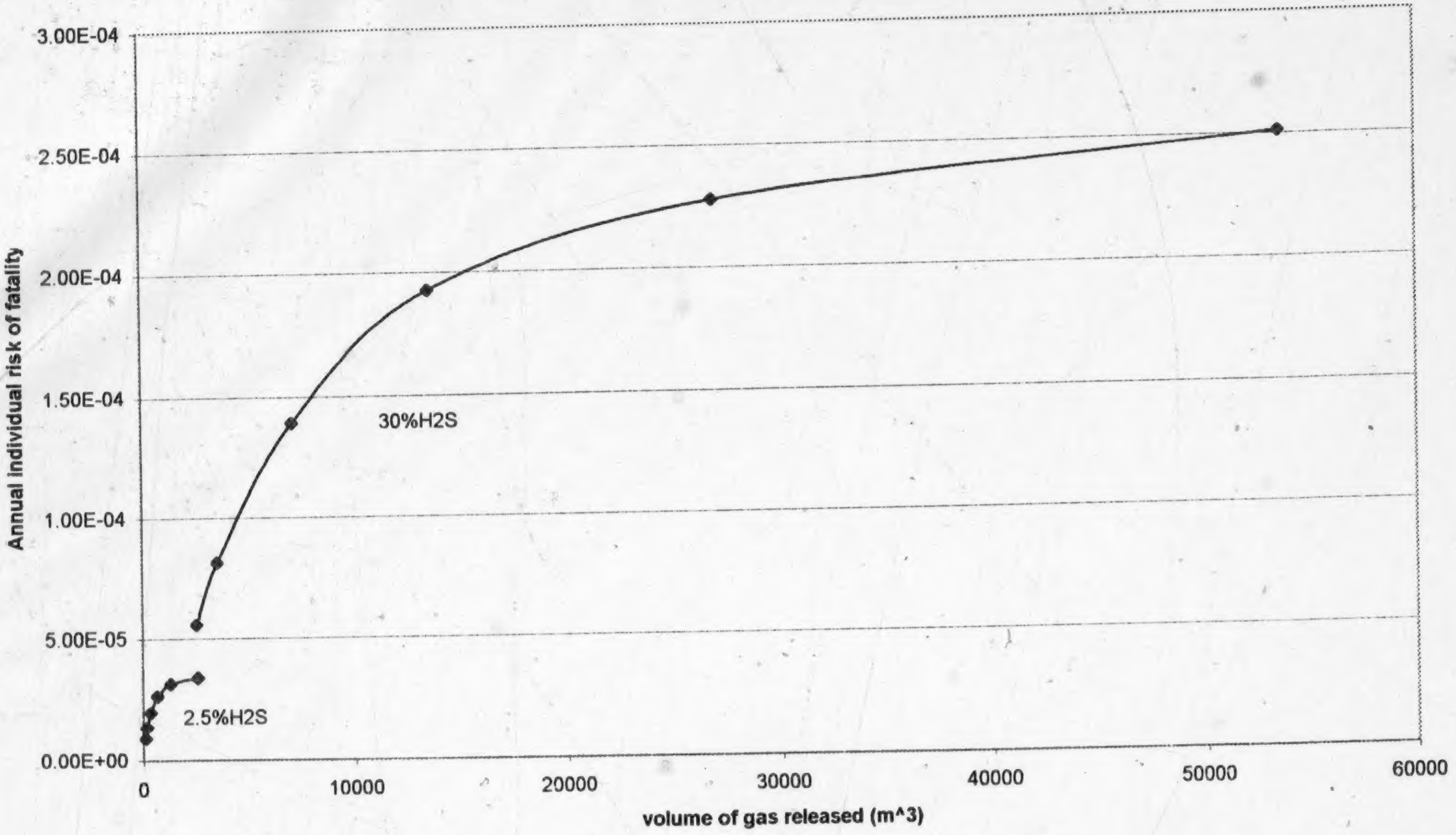


Figure 6.8- Annual risk of fatality while on the ROW vs volume of gas released



6.5 *Societal Risk and FN Curves*

Societal risk is typically presented as frequency vs number of fatality (number affected) (FN) curve, where the x-axis represents the number (N) of individuals who perish and the y-axis represents the cumulative failure frequency (F). FN curves show the annual frequency of events that affect a certain number of people versus the number of people affected during a given event. The FN curves show the maximum number of people affected in a worst-case event and the corresponding frequency of that event, they also show the frequency of the events which could affect at least one person (Concord, 1993). As societal risk is a relationship between event frequency and the number of people harmed, it is a function of the number of people in proximity to the facility. Societal risk can show the frequencies of accidents with multiple fatalities, which may be unacceptable for a society. The risk is derived from the product of the event frequency (pipeline rupture event/year) and the consequences of the event (fatalities/event) (ERCB, 1990). The consequence term, measured in fatalities/event, assumes a continuous population density (population/unit area) and continuous receptors in order to establish the number of potential fatalities. The population density has a limiting or asymptotic effect on the number of potential fatalities (i.e. when all of the surrounding population have perished no other fatalities will occur, as there are no other potential receptors available). Historically FN curves have been presented in a log-log format in order to accommodate the ranges of frequencies and consequences over a wide range of values.

For the purposes of this risk assessment the FN curves depicting societal risk were generated using the Shell Global Solutions "PRTlite" package. The required inputs for this program are: the distance to a probability of fatality of 1%, the setback distances, the screening level meteorological conditions, and the population density.

Figure 6.9 shows the FN plot for the 10000m segment of the 30% H_2S in a developed rural area where the population density is $5.0\text{x}10^{-5}$ people/m^2. The setback distance applied to this case was a 100m exclusion zone. Outside of the exclusion zone the population density was assumed to be $5.0\text{x}10^{-5}$ people/m^2.

Figure 6.9 shows the asymptotic nature of the curve as it is limited at a frequency of $1.6\text{x}10^{-3}$ events per year at one end and at 60 fatalities for a given failure event number regardless of the frequency of fatalities. The parallel lines on the graph are lines of equivalent FN (each point along each line has an equivalent FN value). The lines are drawn on the societal risk plots are an indication of risk levels (negligible risk ($\text{FN} \leq 1\text{x}10^{-5}$), risk reduction desirable ($1\text{x}10^{-5} \leq \text{FN} \leq 1\text{x}10^{-3}$) and unacceptable risk ($\text{FN} \geq 1\text{x}10^{-3}$). These lines are not regulatory standards, rather they have been preset in the Shell Global Solutions PRTlite modelling package as representative risk values and they can be changed by specific users to be set at any level deemed to be a reflection of societal risk acceptance.

The FN curve presented (30% H_2S, population density $5\text{x}10^{-5}$ people/m^2, 100m setback, 10000m valve spacing on the pipeline) passes through each of the three risk categories. When the curve is in the unacceptable risk zone the annual failure frequency is greater than $1.8\text{x}10^{-5}$ failures/km. If the setback distance was greater than 100m there would be fewer people affected at the different failure frequencies. The annual failure frequency is $7.45\text{x}10^{-4}$ failures/km, as used in the risk calculations, which is greater than the failure frequency identified. To avoid the unacceptable risk zone the setback distance needs to be greater than 100m or the segment length of the pipeline needs to be shorter (facilitated through the installation of line break valves or ESDs). The curve presented is one of a series, provided in Appendix 4, which illustrate the calculation iterations required over varying setback distances and pipeline segment lengths in order to achieve a risk curve that might be deemed acceptable. The example selected for inclusion in the text is illustrative of an unacceptable case; the risk values in this case could be lowered through the increasing of the setback distance or the decreasing of the pipeline segment length.

The population density of the area surrounding the facility drives the shape of the curve. The reason for plotting the FN curves on a logarithmic scale is because of the wide range of frequencies and potential fatalities involved. For the risk assessment on the hypothetical pipeline the range of the number of fatalities is three orders of magnitude, a range that can be plotted with relative ease on a linear scale. The curve (10000m segment of the 30% H_2S in a developed rural area where the population density is $5.0\text{x}10^{-5}$ people/m^2) was re-plotted on a semi-log scale and is presented as Figure 6.10. The curve plotted in the semi-log format has less of an asymptotic shape, and although the population density continues to be a factor limiting the number of fatalities the lower portion of the curve has a shape that is more distinct.

Figure 6.9 - FN Curve for 30% H2S, Developed rural population density, 100m setback, 10000m valve spacing
(Curve developed using Shell Global Solutions PRTlite software package)

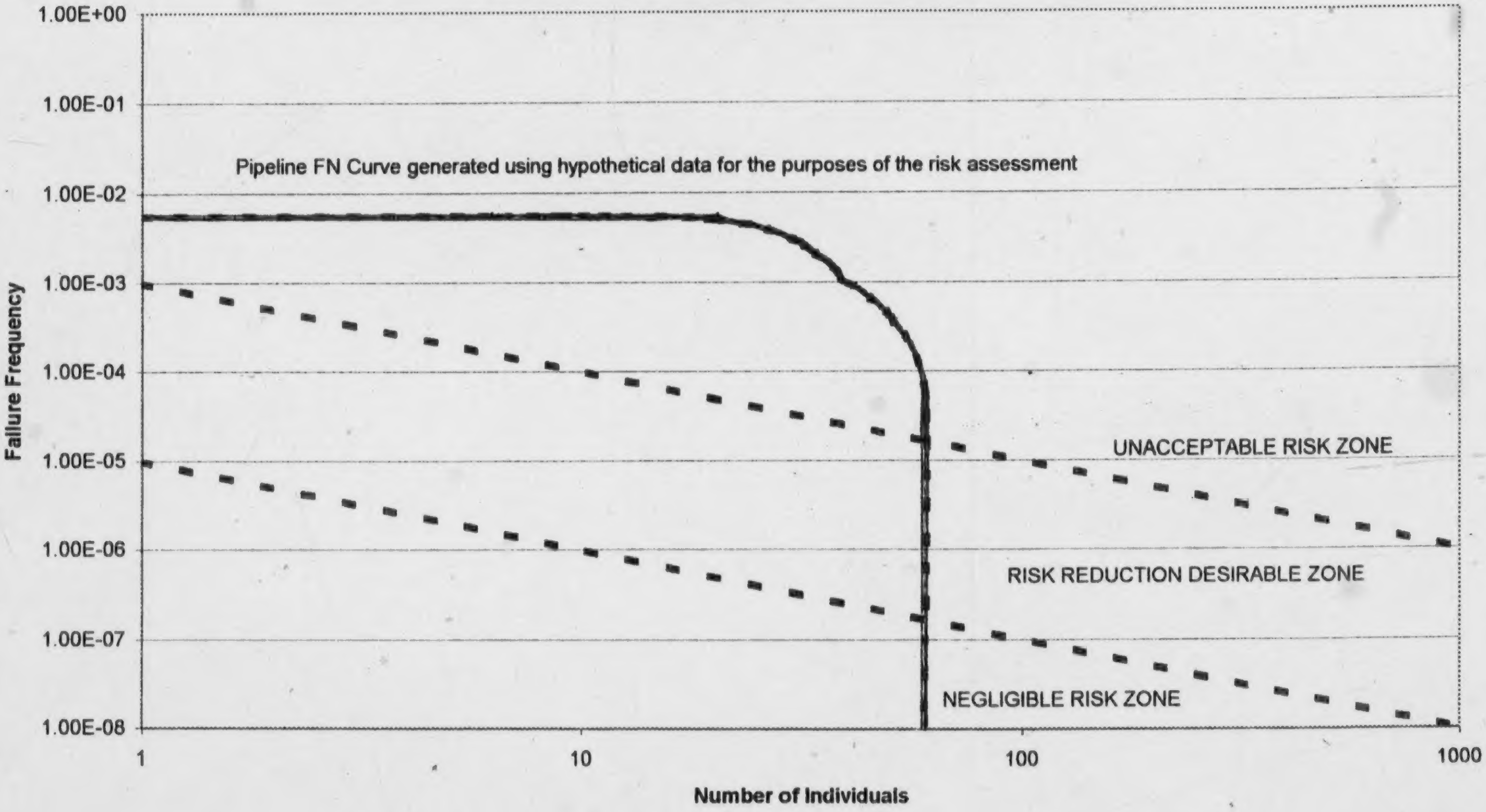
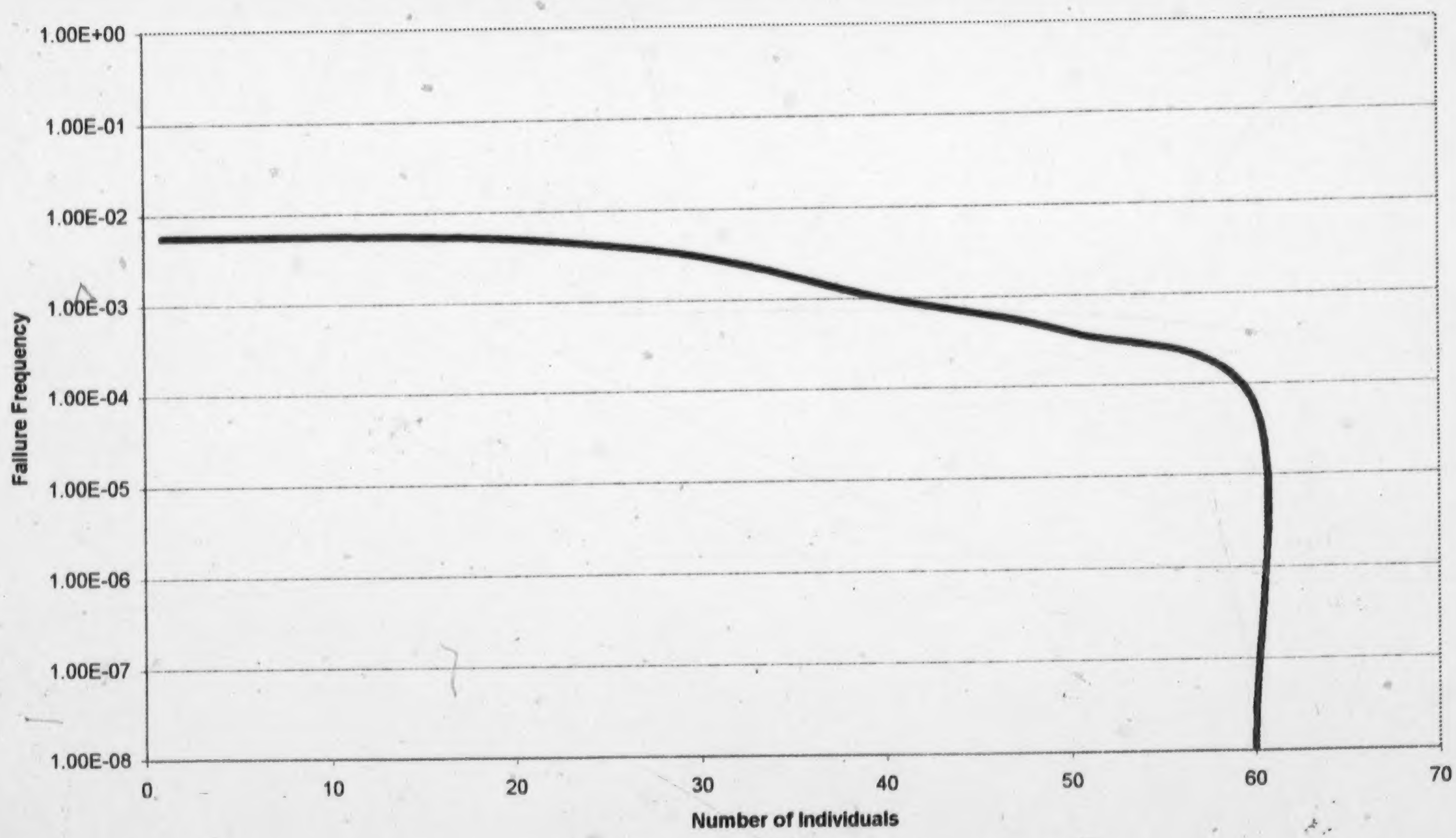


Figure 6.10 - 30% H2S Developed rural population density, 100m setback, 10000m spacing



The low population density in the vicinity of some of the rupture scenarios caused there to be no FN curve for some rupture scenarios, indicating that outside of the setback or exclusion zone there would be no fatalities for release events modelled. The FN curve is only applicable to the area outside of the setback zone.

Table 6.4 details the population densities in the Province of Alberta. Three different densities were used for the determination of the societal risk: rural, developed rural and urban.

Table 6.4 Population densities in the Province of Alberta

Exposed Area	**People/hectare (Concord, 1993)**	**Population Density (people/m^2)**
Rural - individual dwellings	0.01	1.0×10^{-6}
Developed Rural	0.5	5.0×10^{-5}
Average urban	10	1.0×10^{-3}

Table 6.5 shows the data from the FN curves for the rupture scenarios in the risk assessment. The data in Table 6.5 also show how reducing the segment length of a pipeline (inserting more ESD or line break valves) can reduce the risk associated with the pipeline. The FN plots for all of the scenarios presented are presented in Appendix 4.

Table 6.5 Societal Risk Data from FN curves

Gas Conc. (%H_2S)	Segment Length (m)	Population Density (people/m^2)	Required Setback Distance (m)	Frequency Failure intercept	Maximum number of people affected
2.5	All lengths	$1x10^{-6}$ rural	100	No curve	No curve
2.5	All lengths	$5x10^{-5}$ dev. rural	100	No curve	No curve
2.5	All lengths	$1x10^{-3}$ urban	1500	No curve	No curve
30	All lengths	$1x10^{-6}$ rural	100	No curve	No curve
30	500	$5x10^{-5}$ dev. rural	100	$2.0x10^{-3}$	4
30	1000	$5x10^{-5}$ dev. rural	100	$5.0x10^{-3}$	9
30	2500	$5x10^{-5}$ dev. rural	100	$5.0x10^{-3}$	20
30	5000	$5x10^{-5}$ dev. rural	100	$6.0x10^{-3}$	40
30	10000	$5x10^{-5}$ dev. rural	100	$6.0x10^{-3}$	60
30	20000	$5x10^{-5}$ dev. rural	100	$6.0x10^{-3}$	70
30	500	$1x10^{-3}$ urban	1500	No curve	No curve
30	1000	$1x10^{-3}$ urban	1500	No curve	No curve
30	2500	$1x10^{-3}$ urban	1500	$2.1x10^{-5}$	10
30	5000	$1x10^{-3}$ urban	1500	$1.0x10^{-3}$	100
30	10000	$1x10^{-3}$ urban	1500	$2.0x10^{-3}$	300
30	20000	$1x10^{-3}$ urban	1500	$3.0x10^{-3}$	400

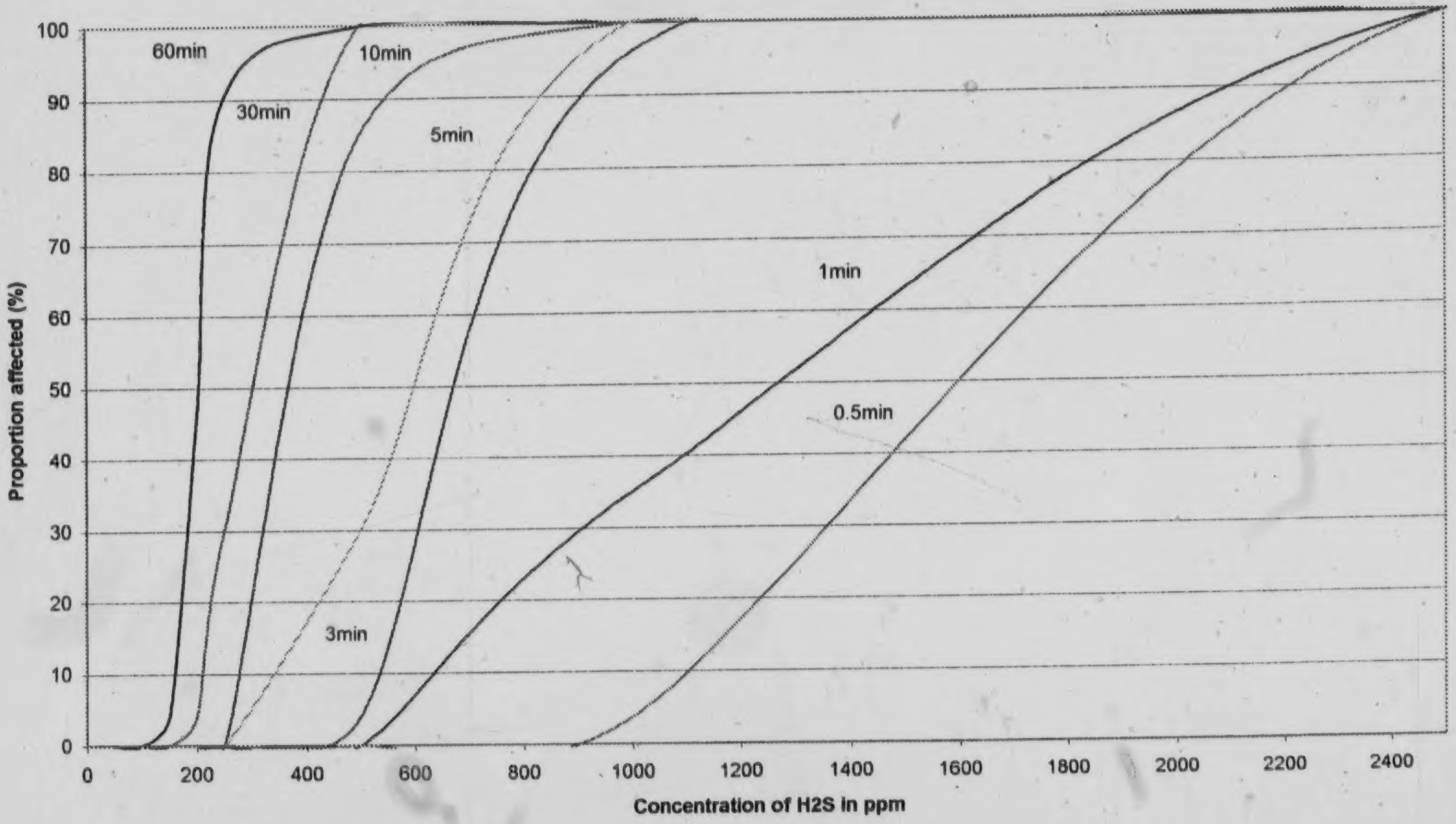
6.6 *Integration of exposure/toxicity assessment*

The population response from any H_2S release is a combination of concentration and time exposure that is commonly expressed as toxic load. The toxic load equation $L=C^nt$ is integral to the Triple Shifted Rijnmond probit equation - Equation 2.

$$(P = -36.2 + 2.366*\ln(C^{2.5}t)) \qquad [2]$$

Figure 6.11 is a series of curves based on the effects of varying concentrations over fixed time intervals calculated using the TSR equation. Time periods of 1 hour, 30 minutes, 10 minutes, 5 minutes, 3 minutes, 1 minute and 30 seconds were held constant as H_2S exposure concentrations were varied between 2 and 10000ppm. The data are provided in Appendix 5.

Figure 6.11 - Lethality Curves (based on the TSR) for varying exposure times



The probit values achieved were converted into percentage of the population responding using the Rijnmond Public Authority methodology (Rijnmond Public Authority, 1982). These curves show a lack of variability in the population response. (e.g. There is effectively a step response in the dose response curve. The 60 minute time curve indicates that there would be no fatalities in the population for 60 minute exposures to concentrations of 100ppm, 90% fatality levels for exposures of 200ppm for 60 minutes and 100% fatality levels for exposures of 400ppm for 60 minutes). The profile of the 30-second exposure curve also causes some questioning with 0% fatality response at an exposure of 900ppm for 30 seconds and 100% fatality response at an exposure of 2500ppm. While these data allow for the generation of a classic S shaped dose-response curve, different times should show more variability in responses. Layton and Cederwall (1987) concluded from their review of health-effects literature that a concentration of approximately 300ppm represented a threshold for lethality during exposure periods of about 10 minutes, this expectation is not reflected in the curves of Figure 6.11 which suggests an expectation of substantial mortality (>50%) for an exposure of 300ppm for 10 minutes.

As summarized by Guo (2001) the human data for response to H_2S is more varied than the animal data and is much sparser because of ethical restrictions on human experimentation. The human data result from post exposure extrapolation of accidental doses which is less accurate than lab experimental data; the method of exposure assessment then becomes a predictive exercise with the toxicological data unavailable for validation. The techniques employed in the early toxicological investigations performed on dogs and rats in the 1920s are no longer utilized. Current toxicological studies utilize physiologically-based pharmacokinetic (PBPK) models which allow for the study of experimental animals followed by model scale-up using physiology data to translate results to humans.

These calculated responses of the lethality curves, based on the TSR, illustrate some of the weaknesses of the probit equation. The probit equation does not fully account for the variability in population response, highlighting a lack of physiological reality in the toxic load or probit concept. The toxic load curve is used as a fitted curve to accommodate the relevant paucity of experimental data. The lethal concentration of H_2S is known and documented (Table 4.1) however the low-dose responses are not known. In the lower portion of the probit equation curve, where there is an almost zero response from within the population, practicality limits the acquisition of lethality data to substantiate the curve. For example, to substantiate an estimate of a 1 in 100 response 1100 mice at each exposure level would be required to define the response with a 95% confidence interval of +/-0.01 (Cairns, 1980). Thus over 1000 animals are required to be tested at that dose to be able to generate a meaningful statistical estimate of a response distinct from zero.

The probit curves require a defined endpoint as the response to the dose; death is a defined endpoint. The probit response does not consider long-term, low dose exposures for chronic exposures or repeated exposures for cumulative effects. The probit curves may also be less useful for non-lethal endpoints because of the lack of variability shown in the curves for the population response. Conversely less defined sub-lethal effects of exposure may have other causes and their responses may be more variable across the population. Non-lethal endpoints may result from a wider range of concentration and time combinations and may have a wider range of population responses because of the nature of susceptible groups within the population.

7.0 Uncertainty analysis

Uncertainty can be classified as either variability or true uncertainty. Variability (or type A uncertainty) occurs when the quantity cannot be expressed as a single value but actually exists as a number of values depending on time, space or other factors (Finkel, 1990). Variability represents true differences in a population under study with a distribution of values across a population (Hrudey, 2000). In order to deal with variability in risk assessment, the mean and the extreme values of a quantity can be utilized and can be presented as a probability distribution of the true values of a variable quantity (Hrudey, 2000). True uncertainty (or type B uncertainty) is the lack of knowledge about the true value of a particular parameter (in cases where a single true non-variable value exists). The true uncertainty can also be represented as a probability distribution representing the dispersion of the estimates of the true value. True uncertainty can be reduced by gaining more knowledge to improve how much you know about the value, but gaining better information about variability will not reduce it, only a more complete understanding of the variable under study concept will be achieved (Hrudey, 2000). The major sources of true uncertainty in risk assessment are discussed in Table 7.1 (Hrudey, 2000).

Table 7.1 - Sources of True uncertainty (Hrudey, 2000)

Risk component	**Source of true uncertainty**
Hazard identification	Unidentified hazards
	Extrapolation of available data to human receptors
	Confidence in the causal link between exposure and outcome
	Quality of available studies and differing results from the studies
Exposure assessment	Quality of information regarding the exposure parameters
	Fate and transport model errors
	Errors in exposure estimates (duration, frequency of exposure, bioavailability)
Dose-response	Extrapolation from tested doses to estimated human doses
	Low dose extrapolation
	Differing dose-response results
	Exposure routes in tested species
	Population characteristics and susceptible sub-population
Risk characterization	Appropriate choices between alternative approaches
	Numerical estimates and integration of component uncertainties

Finkel (1990) detailed specific sources of uncertainty, those applicable to the use of a model (i.e. a dispersion model) are:

- surrogate variables (when one variable that is difficult to assess is substituted with another that is more accessible);
- excluded variables (the omission of variables that make the model less user friendly or exceedingly complex);
- abnormal conditions (models are applicable in known conditions and tested under ideal conditions, they may be less applicable in extreme or unknown conditions); and

- errors which occur from an incorrect model structure.

There are sources of both true uncertainty and variability in the components of the risk assessment (Bogen, 1995). Each of the discussed variables has an element of both true uncertainty and variability, akin to the perpendicular crossing of two axes one for true uncertainty and one for variability. Although each data point has a combination of the two parameters there can be greater contributions from one rather than the other (Bogen, 1995).

Variables including wind direction and speed, and meteorological stability class can be predicted using historical data to derive the mean and the extreme values which can then be utilized to construct a probability distribution of the true values of a variable quantity. There remains however, an inevitable component of true uncertainty in these variables, because the underlying premise of all probability models is that the future will behave as the past (Rowe, 1994) thus the exact weather or wind condition at an exact point in time cannot be known or predicted with 100% accuracy.

In Figure 7.1 the combination of the uncertainty and the variability in a single variable is illustrated. The x-y axes would be the probability distribution of the true values of the meteorological or wind conditions (the variability), and the z-y axes would be the true uncertainty associated with the point on the variability probability density function, indicating the true uncertainty or the "unknowability" of the term.

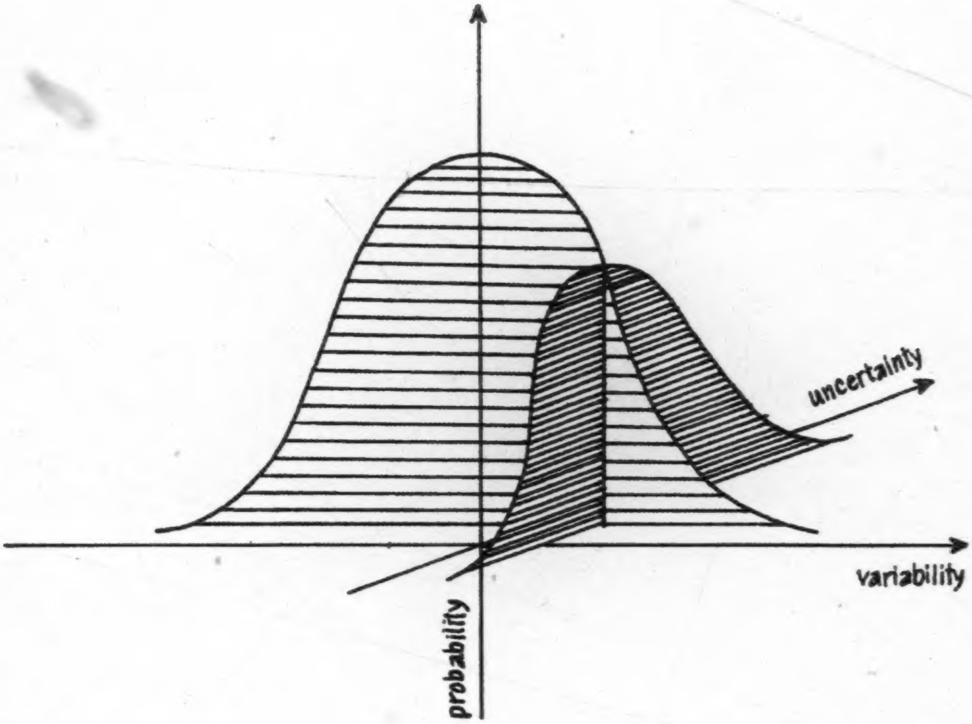

uncertainty
variability
probability

Figure 7.1 – Illustration of Uncertainty and Variability

The terms designated as constants by convention are less uncertain and less variable as they are assigned a value for the purpose of the calculation. In reality there are probability density curves associated with each of the constant values.

In the completion of a risk assessment a distinction must be made between the data that are known and are unknown or assumed, and the assessor's level of confidence in each (Frey, 1992). The strengths and limitations of the data, the model and the resulting predictions or risk estimates are detailed for the pipeline rupture risk assessment. Both qualitative and quantitative details are presented for each variable and descriptions and interpretations of the risk estimates are included. A single risk number cannot accurately represent the multiple dimensions of risk. Likewise a single number should not determine a risk decision because of the uncertainty inherent in every part of the process. Unfortunately, too often risk decisions are based on a single number without an appreciation of the lack of reality inherent in using a single number to represent risk (Hrudey, 2000; Finkel 1990).

In order to determine the level of confidence in the risk estimate, the data was subjected to an uncertainty analysis using a Monte Carlo simulation. A Monte Carlo simulation is a tool which generates a probabilistic risk estimate which performs a large number of repeated calculations using values selected from user defined distributions for input values in order to provide an output distribution to illustrate the uncertainty in the calculated risk estimate. The simulation was completed using a commercially available software package. While the Monte Carlo analysis provides a range of values for the result, the analysis cannot represent all of the uncertainty for the reasons discussed within. In this analysis probability distributions for the true variables, and the range of estimated values for the uncertain variables, were used in order to assess the level of certainty of the resulting value. The probability distributions were inputted by the user and can be user-determined; thus the validity of the answer achieved is only as strong as the validity of the distributions utilized to characterize the input variables.

The simulations run provided a range of values for the annual individual risk estimate, dependent upon the specific conditions for which probability distributions or range of value distributions were used.

Three specific scenarios were modelled for a pipeline with 30% H_2S and a segment length of 20000m (20km):

- The first was the scenario depicted in the risk table (Table 6.2) where the risk was calculated for a specific point in time and space that assumed the receptor was located in the plume, in a rupture, in the vicinity of Central Alberta. (The probability of exposure was assumed to be 100%).
- The second utilized the characteristics of the oval plume, but was not specific to Central Alberta and thus did not utilize specific meteorological data. The calculation spreadsheet is provided in Appendix 2 with the complete data set.
- The third combined all of the variables used in the previous scenarios including meteorological data and an assumption that the probability of exposure was not necessarily 100%.

7.1 Probability Density Functions for Risk Variables

Risk is calculated as the product of the frequency of events and the adverse consequences. The frequencies of events are derived from historical statistics: the frequencies of failures and their types, and the meteorological conditions and prevailing wind direction. Some of probabilities are assumed to have a value of 1.0 and are assumed to be constant (non-ignition and outdoor receptor). The adverse effect of the hazard is taken as being fatality due to sour gas exposure.

Risk=(hazard frequency)*(consequence of the adverse effect) *(interaction length)

The annual individual risk of fatality from a pipeline rupture is the annual chance of an individual dying as a result of a specific rupture event. The value is calculated in this assessment through the products of the contributing frequencies and probabilities. The frequency of events portion of the equation is:

F= (pipeline terms)*(meteorological terms)*constants*interaction length

Where Pipeline terms = (Failure frequency/km*yr)*P(emission rate)*P(release geometry)

Meteorological terms = P(meteorology)*P(wind direction)

Constants = P(non-ignition)*P(outdoor receptor)

The consequences or adverse effects of the hazard are:

P(Adverse effects) = P(fatality)*P(exposure)

The probability of fatality is the probability that an individual exposed to that level of contaminant would die; this is calculated using the Triple Shifted Rijnmond probit equation. The probability of exposure is the probability that an individual at distance (x) from the source would be located within the plume. The probability of exposure is calculated for each individual distance in the risk profile.

The **interaction length** is the distance over which the hazard is applicable; for pipeline ruptures the distance is twice the hazard distance to PD1% in these calculations. (This value must be multiplied into the equation as the frequency term is measured in failures/km*year).

The variables, their values and whether they are true uncertainty or variability are listed in Table 7.2. The values that are set as constants are set by convention and are policy based assumptions chosen on the basis of caution (e.g. the probability of there being an outside receptor =1.0 is an assumption based on caution rather than specific evidence). In the establishment of values as constants the distinction must be drawn between the value being selected based on defensible scientific interpretation of available data (e.g. the speed of sound), or the value being set as constant by choice to ensure an element of caution in the calculation. Even in some of the truly uncertain terms, policy decisions incorporate a level of caution (e.g. the triple shifting of the TSR equation was a policy decision).

Table 7.2- Definition of Variables

Variable	Value	Variable definition
Failure frequency	7.45×10^{-4} km/year	Variability - based on historical frequency
P(non-ignition)	1.0	Assumed value - Constant
P(emission rate)	1.0	Assumed value – Constant
P(release geometry)	1.0	Assumed value – Constant
P(meteorology)	0.21	Variability - based on historical frequency
P(wind direction)	0.28	Variability - based on historical frequency
P(outdoor receptor)	1.0	Assumed value – Constant
P(fatality)	0.01	True uncertainty - based on toxic load (TSR)
Interaction length		True uncertainty - based on toxic load and dispersion model
Plume width (in P(exposure))	15° or 30°	True uncertainty - based on assumptions and dispersion modelling

Each of the variable or uncertain terms for which a distribution of values is used is discussed in Table 7.3.

Table 7.3 - Discussion of Distribution of Terms

Variable	Distribution Selected	Expected value	Minimum Value	Maximum Value
Failure frequency	Uniform		4.62×10^{-4}	1.85×10^{-3}
P(meteorology)	Triangular	0.21	0.07	0.28
P(wind direction)	Triangular	0.28	0.21	0.39
Plume angle	Triangular	30°	20°	45°
P(exposure)	Generated by Monte Carlo	7.02×10^{-2}	6.92×10^{-2}	7.21×10^{-2}
P(fatality)	Triangular	0.01	0.00	1.00
Interaction length	Triangular	2*(0.048*PD1%)	2*(1.0*PD1%)	2*(5.58*PD1%)

The uniform probability density function for the failure frequency term was selected to represent the variability of the failure values because of the historical variability in the number of failures each year. The historical number of failures per year ranges from 7 to 28 (AEUB, 1998, Bercha, 2002). The frequency statistics were determined by dividing the number of failures by the length of sour service pipeline in the Province (15135km). The uniform distribution is used to represent a range of possible values (Cullen and Frey, 1999). The number of failures has shown an increasing trend, however the frequency of failures (both leaks and ruptures together) is relatively stable, as the length of pipeline in the Province is also increasing.

A triangular distribution was used for the representation of the meteorological and wind direction data. These terms are truly variable with components of uncertainty. The uncertainty is derived from the fact that probability based on frequency statistics requires that the future behave like the past (Rowe, 1994). The distributions for each of these terms could be more clearly defined with additional information, however the exact weather and meteorological conditions at a specific time on a specific day cannot be predicted without fault. The triangular distribution used an expected value and upper and lower bounds, these data points were identified from the available data. The probability of a low wind speed meteorological condition was determined through examination of historical records. The low wind meteorological condition ranged between 7% and 28% with an expected value of 21%. The probability of wind direction was also determined through an examination of historical data. The wind direction had an expected value of 28% (which was the percentage of winds from the S-WSW) the range of values was from 21% to 39%.

A triangular distribution was selected for the plume width angle. The probability density function had a minimum value of 20°, an expected value of 30° and a maximum value of 45°. The values were selected from discussions with experienced plume modellers at RWDI West Inc. The plume width is a truly uncertain term and it influences the probability of exposure through its inclusion in the calculation of the minor axis in the oval plume shape.

The probability of exposure is derived from an area calculation which uses the calculated difference between two fractions of the distance to the probability of fatality of 1%, and the tangent of the plume width angle. Because of the inclusion of the distance to the probability of fatality of 1% in the probability of exposure term, these terms were not considered to be independent of each other. Frey (1992) discusses the dependence of variables and indicates that if the uncertainty is primarily due to only one individual variable in a simple model, variables can be stated as input variables even if they are dependent. A Monte Carlo analysis was run for the calculation of the probability of exposure term and the sensitivity analysis indicated that 99.1% of the uncertainty was generated by the uncertainty in the plume width angle. In the Monte Carlo analysis for the annual individual risk calculation the principal contribution to uncertainty was again from one variable (the probability of fatality). Because of the minimal contribution of the distance variable in the probability of exposure term, the term was considered as an independent variable and its uncertainty distribution was generated by the Monte Carlo analysis.

The probability of fatality is calculated using a toxic load equation and probit model. The equation selected by the EUB is the Triple Shifted Rijnmond (TSR) equation, however there are other toxic load equations. The load associated with a probability of fatality of 1% was calculated using probit equations (CCPS, TSR and AEGL-3) and concentration time curves. The toxic load values were then substituted into the TSR equation and probabilities of fatality ranging from 0-100% of the population were calculated. The AEGL-3 model generates results that are orders of magnitude different from the other probit models.

Two different distributions were used for the probability of fatality - the triangular and the uniform. The logic behind the use of the triangular distribution was that the expected value (the PD calculated using the TSR) was substantially closer to the minimum value (CCPS) than to the maximum (AEGL-3). The uniform distribution was also used to reflect the range of potential values that the probability of fatality may have.

The premise behind toxic load is empirical and is based on limited evidence - all of the toxic load studies are performed on lab animals exposed to a constant concentration of H_2S without hydrocarbons in the stream (Wilson, 2002). The range of calculated values demonstrates the levels of uncertainty in the toxic load and probit calculations. No one toxic load equation is entirely defensible on scientific ground. There are a number of different probit equations each with a confidence interval around any calculated value, and the existence of multiple values illustrates the uncertainty in the results. The concentration term itself is determined through the application of a dispersion model. There is also uncertainty in the dispersion model particularly in the determination of the characteristics of the contaminant plume away from the centre line, the concentration values for input to the probit equations are generated by the dispersion model.

The interaction length for the pipeline is the distance over which the impact of the pipeline failure may be experienced. The interaction length is determined through the modelling of the dispersion of the plume away from the rupture. The concentration of the contaminant along the centerline of the plume is calculated based on atmospheric conditions, gas properties and pipeline characteristics and then integrated into a toxic load model. The dispersion of the contaminant or its concentration varies proportionately with the inverse of distance. The three toxic load models were plotted against the fraction of distance in order to determine an approximate range of values for the interaction length. A triangular distribution was selected to represent the distribution of values. The expected value was the interaction length as calculated using the TSR equations and the minimum and maximum values were representative of the CCPS and AEGL-3 equations respectively.

The use of the Poisson distribution for the study of the pipeline failure rates is discussed in Section 7.2. When the Poisson distribution was input as the probability distribution of the pipeline failure rate value values in the Monte Carlo simulation the data was heavily skewed towards a zero value, perhaps because the

Poisson function is an exponential decay function. For the purpose of the risk assessment the uniform distribution was selected.

7.2 *Poisson distribution of pipeline failures*

The historical pipeline failure data for sour service pipelines in the Province of Alberta between 1980 and 2002 (AEUB, 1998, Bercha, 2002) were analysed. The analysis included the total number of failures and the failures related to internal corrosion and attempted to establish the veracity of the available data regarding the establishment of trends. The data were analysed using the Poisson distribution function in order to calculate the Poisson probability. This is the probability that the number of future failures will be less than or equal to the weighted average of the annual failure rate of the past. The historical pipeline failure data were deemed to be suitable for the application of the Poisson function because (Arulanandam et al., 1997):

- There is an assumption that the probability of a failure in any specific kilometer of pipe or year of operation is the same for all lengths and times being observed.
- There is an assumption that all of the units has the same probability of failure and that each incidence of failure is independent of any other. (The failures may not always be independent as often after a single pipeline failure is repaired, the pipeline fails at another location during the pressure test prior to the line returning to operation. These additional failures are due to the fact that during the pressure test the line is tested with water or gas at a higher pressure than that at which it is operated.)

- The potential number of failures is unlimited.
- The failure events are relatively rare and each can be considered a discrete random variable. (As there are true values for the variables a probability mass function is generated as opposed to a probability density function.)

The Poisson probability is the probability that the next year will yield failure events less than or equal to the weighted average. The analysis of the failure data indicated a high probability of future failure events (P=82.3% that the number of failures from all causes will be ≤ 18.39). Through the Poisson analysis of failure data the conclusion can be drawn that in any given year there is a negligible chance that there will be zero pipeline failures. The data for the Poisson analysis of the failure data is presented as Appendix 5.

7.3 Monte Carlo Uncertainty Analysis

The Monte Carlo simulation utilizes user-defined probability distributions for input variables to generate a sophisticated picture of the uncertainty in a given calculation. While Monte Carlo simulations can be used to delineate the uncertainty in the risk estimate the analysis cannot represent all of the uncertainty. Three different scenarios were simulated. Values were calculated using point estimates for two of the scenarios. The Monte Carlo simulation provided a range of values for these point estimates using the probability distributions input for the variables in the risk calculation. Table 7.4 shows the comparison of the results.

Table 7.4 Comparison of Risk Estimates

Case	Calculated Risk Estimate	Mean Value (Monte Carlo)	Range of Values (Monte Carlo)
Annual individual risk of fatality as calculated at the point of PD1% with probability of exposure P(exp) =100% considering specific meteorology	2.5×10^{-6}	2.8×10^{-4}	1.7×10^{-7} to 2.8×10^{-3}
Annual individual risk of fatality as calculated using an oval plume for PD1% and $1 \leq P(exp) < 100\%$ without consideration of meteorology	3.0×10^{-10}	3.3×10^{-8}	1.8×10^{-10} to 2.1×10^{-7}
Annual individual risk of fatality as calculated using the oval plume for PD1% and $1 \leq P(exp) < 100\%$ considering meteorology	1.2×10^{-10}	1.4×10^{-8}	1.6×10^{-11} to 1.3×10^{-7}

The strength of the Monte Carlo tool is in the utilization of distributions of variability for known values of parameters instead of a point estimate for the value (Hrudey, 2000). For truly uncertain terms where the user determines the probability distribution the results generated through the use of the simulation are only as valid as the distributions used for input.

Numerous distribution profiles have been characterized for exposure factors that are frequently used in health risk assessments (Finley et al., 1994). These factors are widely used and individual cases can be checked for validity through the existence of extensive databases. For some of the more unique terms used in analyses, published distributions do not exist and therefore must be user defined.

The use of the Monte Carlo simulation requires the independence of the input variables. When dependent variables are used the effectiveness of the model is diminished. Variables that are dependent can be expressed in terms of other independent variables or their contribution to overall uncertainty can be determined (Frey, 1992). In a simple model dependent variables can be used as input variables if there is another single variable that is the principal contributor to uncertainty (Frey, 1992, Cullen and Frey, 1999). In the case of the pipeline failure risk assessment and uncertainty analysis the probability of fatality variable, as derived from the toxic load probit equations, was the principal contributor of uncertainty.

In the case of the pipeline rupture risk assessment the Monte Carlo analysis was a useful tool in determining a range of possible risk values in each scenario, but as with the case of the point estimates, the distribution and range of values used was also largely based on assumptions. Data from the Monte Carlo runs are provided in Appendix 7.

7.4 Sensitivity of exposure variables (Monte Carlo analysis)

A sensitivity analysis uses the uncertainty ranges defined for each of the variables and determines the effect of the parameter uncertainty in the variance of the overall risk variable (Hrudey, 2000). The manner in which the risk calculation was performed enabled the principal contributors to the sensitivity analysis to be identified and illustrated that the probability of fatality was the principal variance. The contribution of the probability of fatality in all of the cases was in excess of 50%. When the distribution for the probability of fatality was changed from triangular to uniform the contribution of the probability of fatality was still the principal contributor to the overall variance at ~ 50%. The sensitivity analysis showed the impact of uncertainty contributed from the toxic load models and the understanding of the toxicology of H_2S.

8.0 Risk Description and Shortfalls

In assessing the annual individual risk of fatality from a pipeline failure there is a need to distinguish the risk to ***any*** individual from the general population who may be exposed from the risk to a ***specific*** individual, the risk to a specific individual will be substantially less than the risk to any individual. The risk to any individual from the general population is higher based on the premise that there is a constant receptor - regardless of the timing or location of the leak there is a receptor assumed to be in place who will be adversely affected.

A pipeline in the Edmonton area may have an annual individual risk of fatality associated with a rupture of $1.0x10^{-6}$ for any individual; however the specific risk to Mr. X who lives in Calgary, and never travels to Edmonton, is zero, while the risk to Mr. Y who passes the pipeline on his commute to and from work may be $1x10^{-10}$ (Mr Y. is a specific individual). Alternately if the Lotto 649 is considered, it is certain that someone will win the jackpot (the certainty is based upon the carrying over of the jackpot from week to week and the reliability of the lottery corporation as a public trust). Thus the probability that someone will win = 1.0, however the chance that a specific ticket held by a specific individual, Mr. X will win is $\frac{1}{49} x \frac{1}{48} x \frac{1}{47} x \frac{1}{46} x \frac{1}{45} x \frac{1}{44} \approx \frac{1}{10,000,000,000} = 1x10^{-10}$. $1x10^{-10}$ is equivalent to 1 chance in 10 billion for Mr. X's specific ticket to win the lottery.

With respect to the pipeline failures, the difference between risk to any individual and risk to a specific individual is described.

Risk to any individual - Two cases are used to describe the risk to any individual, the difference between the cases being in the probability of exposure. In the first case it is assumed that at any geographic location of the pipeline failure there will be a receptor, thus the probability of exposure is 100%. The receptor is assumed to be a continuous receptor (24 hours/day 365 days/year), and is guaranteed to be exposed. In the second case the probability of exposure is not assumed to be 100%, rather it is based on the location of the receptor within the plume; in this case it is also assumed that there is a continuous receptor. These risks are calculated to determine the risk to any individual. The two risk scenarios are:

1) Probability of fatality of 1%, probability of exposure 100% and specific meteorological and wind direction conditions; and
2) The probability of fatality with a probability of exposure between 1 and 100%.

In the second case the details of the plume are not known and while the meteorological conditions can be added for a specific location, the second case is more representative of a risk situation which might be presented to an audience of stakeholders. If there were a continuous receptor population on the border of a circle with a radius of PD1% less than 10% of receptors would be exposed if there was a pipeline rupture (using a calculation incorporating both radius and plume angle to determine the arc length and then determining the arc length as a proportion of the entire circumference).

In case 1, for the risk assessment where the probability of exposure is assumed to 100% and the probability of fatality is 1%, the annual individual risk of fatality resulting from a pipeline rupture is between 9.3×10^{-8} and 3.4×10^{-7} for a 2.5% H_2S line with segment lengths between 500 and 20000 meters. For the 30% H_2S line the annual individual risk values range from 5.6×10^{-7} to 2.5×10^{-6}. In these cases the probabilities for specific meteorological conditions have been included in the event probabilities.

In case 2, the probability of fatality is 1% and the probability of exposure is between 1% and 100%, and the same assumptions were made with respect to the pipeline and release characteristics as in case 1. The probability of exposure is not assumed to be 100% rather it is determined by the distance the receptor is away from the source. The plume is assumed to be oval in shape at ground or receptor level. The risk values are not moderated for meteorological and wind conditions rather the probability of each is assumed to be 1.0 (the wind is from the direction that has the most low winds and the meteorological conditions are stable). The annual individual risk of fatality from a pipeline failure at a distance from the pipeline corresponding to the PD1% distance ranged from $1.1\text{x}10^{-11}$ to $3.9\text{x}10^{-11}$ for the 2.5% H_2S line and from $6.6\text{x}10^{-11}$ to $3.0\text{x}10^{-11}$ for the 30% H_2S line. If the specific meteorological and wind direction probabilities were included in the risk calculation the risk values would decrease further. The **(1)** distances from the pipeline to a 1% probability of lethality and the associated annual individual risk of fatality for the **(2)** ~~100~~% probability of exposure and the **(3)** probability of exposure between 1% and 100% cases are summarized in Table 8.1.

Table 8.1 - Distance from the pipeline to a maximum 1% probability of lethality and Annual Individual risk at that point

% H_2S	Segment Length (m)	(1) Maximum distance to a 1% probability of lethality (m)*	(2) Annual individual risk of fatality at the distance PD1% with P(exp)=1.0**	(3) Annual individual risk of fatality at the distance PD1% with P(exp)=0<x<1**
2.5	500	107	9.3 x10^{-8}	1.1 x10^{-11}
	1000	159	1.4 x10^{-7}	1.6 x10^{-11}
	2500	229	2.0 x10^{-7}	2.3 x10^{-11}
	5000	307	2.7 x10^{-7}	3.1 x10^{-11}
	10000	363	3.2 x10^{-7}	3.6 x10^{-11}
	20000	390	3.4 x10^{-7}	3.9 x10^{-11}
30	500	641	5.6 x10^{-7}	6.6 x10^{-11}
	1000	935	8.2 x10^{-7}	9.6 x10^{-11}
	2500	1600	1.4 x10^{-6}	1.7 x10^{-10}
	5000	2200	1.9 x10^{-6}	2.3 x10^{-10}
	10000	2610	2.3 x10^{-6}	2.7 x10^{-10}
	20000	2880	2.5 x10^{-6}	3.0 x10^{-10}

*Distance values in the table have been rounded to 3 significant figures.
**Risk values have been rounded to 2 significant figures.

Risk to a specific individual - The risk to a specific individual involves integrating the specific individual's potential exposure into the risk equation.

The major unknown in the risk associated with a pipeline failure is the location at which the pipeline will fail; a quantity that is essentially unknowable. For the purposes of the hypothetical pipeline for which the risk assessment was performed the population density of 1 family (4 individuals)/quarter section (160 acres) was assumed. In the settlement geography of rural Alberta the quarter section is a square and has an area of 0.5 mile*0.5 mile (804.5m*804.5m). This corresponds to a rural population density of 6.2 people/km^2 (or 6.2x10^{-6} people/m^2). This population density is between the rural and the developed rural population density values as presented in Table 6.4 which are typical for the Province of Alberta.

Three cases are presented to illustrate the risk scenarios for risk to a specific individual or individuals:

- A family living at the PD1% distance from a 30% H_2S pipeline with a segment length of 1000m;
- A family living at the PD1% distance from a 30% H_2S pipeline with a segment length of 5000m; and
- An individual walking on the pipeline right-of-way for a 30% H_2S pipeline with a segment length of 20000m.

Case 1 - A family of 5 lives adjacent to the pipeline. Their home is located a distance of 965 meters perpendicular from the pipeline but they have a large back yard which, at its closest, is 915 meters from the pipeline. The PD1% distance of 935m cuts through their yard. The width of the yard is 100 meters, and the yard runs parallel to the pipeline. The location of the yard, pipeline and house are shown in Figure 8.1.

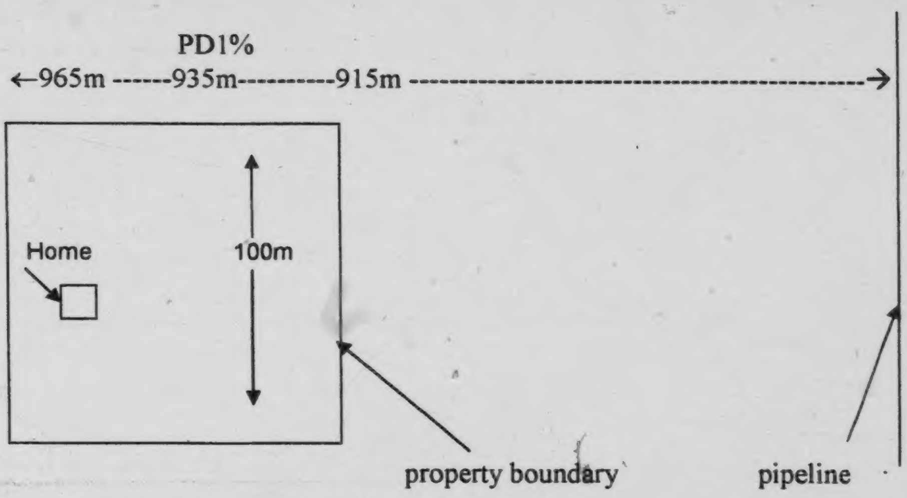
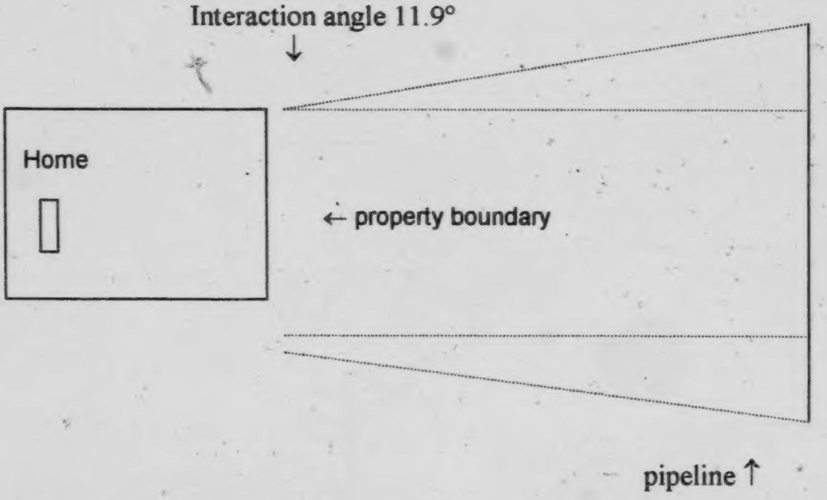


Figure 8.1 - Location of the house and yard relative to the pipeline (NTS)

The pipeline is a 30% H_2S line with a segment length of 1000m operating at a pressure of 10000kPa. From the previous calculations the distance to a location with a 1% probability of lethality during select meteorological and wind conditions is 935 meters (Table 5.8). If the pipeline ruptures there is no guarantee that the contaminant plume will travel in the direction of the home, i.e. there is no guarantee that the probability of exposure in this case will be 100%. The annual individual risk of fatality (as calculated through the use of the risk profile spreadsheet) for a receptor at this distance is 9.6×10^{-11}(Table 8.1). If location specific meteorological and wind direction probabilities (P(wind direction)=0.28 and P(Meteorology)=0.21) are applied to the risk values, the annual individual risk becomes

$(9.6\times10^{-11})*(0.28)*(0.21) = 5.6\times10^{-12}$. With the home being perpendicular to the pipeline, and a segment length of 1000m and a yard-width of 100m, only failures in 484 meters of the pipeline could necessarily affect the family. The interaction angle is 11.9° and the additional length on either side of the 100m length is 192m for a total length of 484m. The interaction angle is illustrated in Figure 8.2. If the rupture happened in any portion of the pipe other than the 484m indicated (i.e. in the other 516m of the pipe segment) the family would be located further than the distance associated with 1% probability of fatality as calculated using the Triple Shifted Rijnmond equation. Probability of a rupture affecting the family $\left(\frac{484}{1000}\right)$=0.48.



The interaction angle is 11.9° and the additional length on either side of the 100m length is 192m for a total length of 484m.

Figure 8.2 - Length of pipeline where a failure may affect the family

The probability of there being an outside receptor can be determined from the daily habits of the family. 2 children attend school (8hours/day, 5 days/week), the father works away from the home (10 hours/day, 5 days/week), the mother and the remaining child are away from the home 2 days/week. The family remains indoors during the night (11 hours/day, 7days/week) and are out every Sunday

(4hours/week). During the time that they are home the 2 school age children are outside 1hour/day during the week and a maximum of 10 hours on weekends, the father is outdoors approximately the same amount of time. The mother and the youngest child are outdoors 1 hour on the weekdays, the younger child is outside on weekends, but the mother remains indoors. The receptor status is detailed in Table 8.2.

Table 8.2 - Receptor status (outside)

Receptor	Outdoors time/week	Total available (hours)	Proportion of outside time
2 school age children	30 hours (15 each)	336	0.09
Father	15	168	0.09
Youngest child	15	168	0.09
Mother	7.5	168	0.04

Therefore the probability of there being an outside receptor at the time of a release is 8.9%, because in this case all of the subjects are interdependent and the outside time of one receptor is not independent of the other receptors.

The annual individual risk of fatality for this family living at the distance corresponding to a maximum probability of 1% lethality in the event of a pipeline release under *unspecified meteorological and wind direction conditions* (probabilities of specific wind directions and stable atmospheric conditions were not included in the risk calculation) can be modified from $9.6\text{x}10^{-11}$ to:

Risk = $9.6\text{x}10^{-11}$*P(pipeline rupture will affect family)*P(family has an outside receptor)

= $9.6\text{x}10^{-11}*(0.48)*(0.09)$

$= 4.1\text{x}10^{-12}$

Or the annual individual risk of fatality for this family living at the distance corresponding to a maximum probability of 1% lethality in the event of a pipeline release under *specified meteorological and wind direction conditions* can be modified from $5.6\text{x}10^{-12}$ to:

Risk $= 5.6\text{x}10^{-12}$*P(pipeline rupture will affect family)*P(family has an outside receptor)

$= 5.6\text{x}10^{-12}*(0.48)*(0.09)$

$= 2.4\text{x}10^{-13}$

Under unspecified meteorological conditions the annual individual risk translates to 1 chance in 240 billion that there will be a fatality in the family related to a failure of the pipeline; under specified meteorological conditions the risk is even lower at 1 chance in 1 in 4.1 trillion. The death rate from lightning strikes in Canada in 1994 was 0.38 per million people, that is 11 deaths in 29 million people (Thomas and Hrudey, 1997). The (death rate) 1994 risk of death by lightning strike statistic is 93,000 to 1.5 million times greater than the annual individual fatality risk estimate for a fatality in the family related to a failure of the pipeline. Additionally the risk levels will decrease as the segment length of pipe increases because the probability that the portion of the pipe from the leak originates could affect the family decreases.

Case 2 -If the pipeline in question is now a 30% H_2S operating at 10000kPa with a segment length of 5000m, the distance to the location corresponding to a 1% probability of lethality becomes 2209m.. The family home is now located a distance of 2239 meters perpendicular from the pipeline but they have a large back yard which at its closest is 2189 meters from the pipeline. The width of the yard is 100 meters, and the yard runs parallel to the pipeline. The length of pipe that could affect the family if it were to fail is 688 meters (294m each side of the 100m yard calculated using an interaction angle of 7.72°). The probability that the pipeline rupture will affect the family is (688/5000) = 0.138 approximately 14%.

Using the risk spreadsheet (for unknown exposure status) the annual individual risk of fatality for this family, living at the distance corresponding to a probability of 1% lethality in the event of a pipeline release under unspecified meteorological and wind direction conditions, was initially calculated to be 2.3×10^{-10}. The risk estimate can be modified to:

Risk = 2.3×10^{-10}*P(pipeline rupture will affect family)*P(family has an outside receptor)

$= 2.3 \times 10^{-10} * (0.14) * (0.09)$

$= 2.9 \times 10^{-12}$

This risk is 1 chance in 345 billion that a rupture of the pipe will adversely affect the family. The (death rate) 1994 risk of death by lightning strike statistic is 131,000 times greater than the annual individual fatality risk estimate for a fatality in the family related to a failure of the pipeline. 1 chance in 345 billion is approximately thirty times less than the chances of winning the Lotto 649 when holding a single ticket for the draw.

Case 3 - For an individual standing on the pipeline right-of-way (ROW) at the time of the failure the risk value again can be examined. At any time the chance of the individual standing on the portion of the pipeline that fails is distinctly remote. Assume that the length of a footspan is 1meter - for the 20km segment of pipe the chance that the individual is standing on the pipeline at the exact point of failure is 1 in 20,000; therefore P(exact location) = $5.0\text{x}10^{-5}$ combined into the annual risk statistic, generated by the risk profile spreadsheet (Appendix 2), for a rupture of a 30% H_2S line is $1.2\text{x}10^{-2}$. The annual individual risk of a fatality from being directly above a pipeline rupture is $(1.2\text{x}10^{-2}*5.0\text{x}10^{-5}) = 6.0\text{x}10^{-7}$ or 1 chance in 1.7 million that the line will fail with a receptor at that point. There being a continuous outdoor receptor at the exact point of the failure, combined with the annual risk statistic of fatality due to pipeline failure at that point is less than one in a million. The probability of fatality for that location remains 100% and the probability of exposure is 100% when directly above the rupture point. While this risk calculation is for any individual, the calculation for a specific individual would be for an individual who lived on the pipeline right of way directly above the pipeline - this is not a realistic scenario because of the imposition of setback distances as regulated by the EUB.

The risk for any individual living 100% of their time on the pipeline right-of-way is greater than for a specific family living nearby a pipeline; but because of imposed setback distances the scenario is totally unrealistic and improbable. While there continues to be discussion regarding the appropriate setback distances (Provincial Advisory Committee on Public Safety and Sour Gas, 2000), the existing setback distances are achieving quantifiable reduction in risk estimates. The EUB do not present any numerical risk estimates in combination with the existing setback distances (AEUB, 2000) rather risk reduction estimates are left to intuition.

The plume of contaminant from a pipeline rupture varies distinctly in concentration from the source to its outer edge. The annual individual risk of fatality at any location from the source varies considerably. For the 30% H_2S line with a segment length of 20km the risk of fatality varies from 1.2×10^{-2} (1 in 85) at source to 3.0×10^{-10} (1 in 3 billion) at the point of PD 1%. The probability of exposure to the plume varies from 100% if located at the source to 7% if located at a distance corresponding to the PD1%. The plume could be compared to standing in a rockslide. At source there are many rocks of all sizes (mostly big ones) and the chances of being hit by any rock are high. At a distance from the slide there are still many rocks but the larger ones have already fallen. Although the area over which the rocks are falling is greater, the rocks are landing with less impact (and are therefore less dangerous). At the end of the slide the smaller rocks are trickling down, there is a chance of being hit by a smaller rock but the consequences are reduced because the majority of the big (and more dangerous) rocks have fallen already and those that are left are less lethal.

The toxic plume may also be considered in relation to the risk of death on the ground from an airplane accident. The annual risk of fatality for those on the ground associated with air accidents has been estimated to be 1.0×10^{-4} at the end of the runway and around the perimeter of a city airport (lifetime risk = 7.0×10^{-3}) (Thompson et al, 2001). The risk then decreases as the distance from the airport increases with the risk being highest within 2 miles of the airport. There remains a higher concentration of risk along flight paths into city airports (areas with increased air travel overhead). Goldstein et al. (1992) estimated the lifetime risk of fatality to groundlings from airplane accidents as 4.2 x10^{-6} (annual risk = $\left(\frac{1}{70}\right)x\left(4.2x10^{-6}\right)$ = 6.0 x10^{-8}). Goldstein et al (1992) does not consider the higher risk in the near vicinity of an airport. The annual risk to the general population (those not located in the vicinity of an airport) is 1.3x10^{-8} when the near airport risk values are eliminated from the averaging calculation (Thompson et al., 2001). By analogy the risk profile associated with fatality to a groundling from an airplane accident is similar to that of the risk profile from a contaminant concentration in a plume - with greater risk near the source (the airport) and declining risk with greater distance from the source or the risk centre line (plume centre line vs flight path).

9.0 Summary of risks

The risks of fatality from a sour gas pipeline failure are difficult to convey owing to the fact that, from the previously described Poisson analysis of pipeline failures, there is a level of certainty that failures will continue to occur; akin to the winning of the lottery by any Canadian. The failure fact is further substantiated by the fact that a proportion of the operating pipelines in Canada are nearing the end of their operational life (Haines, 2002).

Although it is "expected" that at least one of the 15135 km (Bercha, 2002) of sour gas pipelines in Alberta will fail in any given year it is impossible to know which one it will be. There are many people whose daily path crosses a pipeline, or who reside or work in the vicinity of a sour gas pipeline but there is no way to know which individual, if any, may be affected by a failure. The outcome is known, as there will be a pipeline failure, however the exposed population is ultimately unknowable. Should all of the pipeline breaks occur in unpopulated areas of the province, then the exposed population (for acute exposure) would be zero.

Thus, in any given year there will be pipeline breaks and there will likely be individuals exposed to the released gas, the expected outcome. Because the concentration, location or any details of which pipelines will leak or rupture are unknown - (ultimately unknowable), the level of individual exposure and which individuals will be exposed is unknown. Similar risk analogies would include:

- Each year there are a number of avalanches in the Rocky Mountains (a Poisson analysis of the historical avalanche frequency would indicate how many avalanches there may be in the next year). Whether or not there are fatalities as a result of the avalanches depends on whether or not there is a receptor population. No sensible person would ski in the backcountry if a fatal avalanche were guaranteed to happen on that day. The exact timing of an avalanche is unknowable; therefore the receptor population (or the exposed population) is also unknowable.

- In any given day it is known that there will be automobile accidents (including multi-car pile ups, single vehicle accidents and fender-benders), the expected outcome. This outcome is expected through examination of frequency statistics. How can you know as you set out in your car on any given day that you will or will not be involved in a car accident, the unknown exposed population?
- Each week there is a draw in the 6/49 lottery. The money in the lottery is guaranteed to be won (monies not won in one draw are added to the pot for the next draw), the known outcome. When purchasing a lottery ticket it is unknowable whether or not the ticket purchased will be the winning ticket, the unknown exposed population.
- The geographic tracking of the West Nile virus over the last three years has allowed Health Canada officials to expect that there would eventually be cases and more possible fatalities from the disease in Canada - the expected outcome. In summer of 2002 there were 325 diagnosed cases of West Nile virus in Ontario resulting in 18 fatalities (Goldman, 2003). Ontario has a population of 12,068,300 people (Statistics Canada, 2002a); the morbidity rate for West Nile virus in 2002 was $\left(\frac{325}{12,068,300}\right) = 2.7\text{x}10^{-5}$ or 2.7 per 100,000 people. The

death rate from West Nile virus was $\left(\frac{18}{12,068,300}\right) = 1.5\text{x}10^{-6}$ or 0.15 per 100,000 people. The majority of the Canadian population receives at least one mosquito bite each summer (the transmission vector of the virus); the unknown exposed population are the individuals who contract the disease.

- It is a known fact that asteroids and meteorites have collided with the Earth. Analysis of frequency statistics enables the prediction that in the future there will be collisions between our planet and other cosmic bodies (Lewis, 1996, Giorgini et al., 2002). While an impact can be predicted with relative certainty, the location and magnitude of the impact remain unknown. The unknown exposed populations are those in the vicinity of the impact; the extent of the population exposure will be determined by the magnitude of the impact. Some impacts are predicted to cause global catastrophe and would be capable of making the Earth uninhabitable for humans (Lewis, 1996). The data on which the predictions are based have components of both variability and uncertainty. The variability derives from the use of frequency statistics to predict the future from the past (Rowe, 1994). The uncertainty originates from the true lack of knowledge associated with the galaxy, the orbits of the other galactic bodies and the exact position of Earth on its axis and within its orbit at the time of the predicted collision (Giorgini et al., 2002).
- During airplane accidents fatalities on the ground can occur. Each year there are a number of airplane accidents (both Poisson and frequency analyses could be performed to determine how many airplane accidents there may be in the year), the specific air accident or accidents are unknowable yet if the accidents occur

in populated areas there will likely be groundling casualties. This receptor population is unknowable, however analysis of frequency statistics has enabled the annual individual risk of groundling fatality from an air accident to be estimated at 6.0×10^{-8} (Goldstein et al., 1992).

While it is necessary to calculate risk values utilizing the same methods and assumptions throughout the oil and gas industry, in order to have comparable results, external to the industry, it must be questioned as to whether the assumptions are realistic. The continuous outside receptor may be a realistic scenario for pipelines which border urban centres or high traffic rural areas, but many new gas developments are in remote unpopulated areas.

Much of the current gas development is in sour gas. The depleting sweet gas reserves have spawned new exploration in sour gas reserves, both slightly sour gas near urban centres (Manhattan Resources at Ardrossan) and highly sour gas at the edge of the Rocky Mountain foothills (Shell Canada at Ferrier, Rocky Mountain House). The proposed development of these new wells and the heightened public sensitivity to sour gas, has caused the examination of the risk values and particularly the Emergency Planning Zones (EPZs) established around the developing and operating wells and facilities (AEUB, 2002).

Erring with risk estimates to be more cautious (overestimation of risk) does not affect the risk inherently associated with a facility; the risk is simply stated as being greater than it is. Whether this apparent caution in estimating risks allays the fears of local residents should be examined. Cautious overestimation of risk may simply increase fear, whereas demonstrated caution in managing risks should be reassuring.

9.1 *Risk management vs risk issue management*

If oil and gas companies are overstating the risks associated with their facilities does this action serve to manage the risk associated with the facility? Once the risks associated with a facility, in this case a pipeline, have been identified and their numerical significance determined, the company must examine those risks in order to establish how they will be managed. Some risk management options for a pipeline involve internal corrosion monitoring or the use of smart pigs (inter-pipeline tools that can sense differences in the pipe thickness) in order that segments of pipe requiring replacement can be identified before they fail. SCADA systems (supervisory computer aided data acquisition) monitor pipeline pressures and flowrates and emergency shutdown values are triggered to fail closed upon a predetermined decrease or fluctuation in line pressure. Routine maintenance and inspection of valve stations and above ground pipelines can also serve to manage the risk of failure. When or if the line does fail it is the emergency evacuation or sheltering notification procedures that are integral to the minimization of exposure.

Does assuming a continuous outdoor receptor, and thereby overestimating the expected risk of the facility on paper, minimize or increase the requirement for risk management actions on the part of the operating company? Perhaps if the expected risk was represented more accurately, active risk issue management would be necessary in order to present the information that the facilities may not be as hazardous or harmful as initially thought (Leiss, 2001).

Risk management seeks to assess and control the hazards that generate a risk, while risk issue management responds to public controversy about the adequacy of the risk management measures. Risk issue management reflects the fact that the risk issues are not driven by the state of scientific risk assessment alone, rather the risk assessment is just one part of a multi-faceted issue (Leiss, 2001). In both the SARS (severe acute respiratory syndrome) crisis in Ontario and the mad-cow or BSE (bovine spongiform encephalopathy) case in Alberta, the risk estimates for the general public have been presented as very low. Management of the risk issue is now required to mitigate the economic cost of BSE in Alberta and SARS in Ontario which are being driven by responses that are not commensurate with the expected level of the risks. Risk issue management will serve both to address the public confidence with respect to the risk measures taken in each situation, and to attempt to generate an appreciation that the scientific risks are understood and the risk reduction measures being taken exceed the level necessary to manage the risk successfully.

The EUB is faced with both risk management and risk issue management with respect to the hydrogen sulphide content of the developable reserves of oil and gas in Alberta. If the risk estimates generated by the Board are artificially high, through the assumptions that are made and the manner in which the risk estimates are presented, does this contribute to increasing fear of sour gas development? Does the adoption of precautionary risk estimates aid in the public understanding of the issues surrounding the development of sour resources? If the EUB were to establish and publish an optimum risk target that they sought for operations and facilities to achieve, operators could address the risk issue with data indicating how the reference risk levels had been achieved and then bettered. The EUB do enable risk reduction through their mandated setback distances and operating protocols, however the tangible measures that can change (reduce) risk levels need to be clearly identified distinct from the communication measures required to deal with how people react to published risk levels.

The understanding that sour gas kills, should not automatically translate into sour gas pipelines kill. Although there is a considerable length of sour service pipeline in the Province, and the failure rate is tangible, for a person to end up as a fatality that specific person needs to be in the wrong place at the wrong time. Limiting this exposure requirement has been successfully mitigated to date through mandating of short pipe segments and setback distances. This achievement is evidenced by the lack of fatalities in the general public associated sour gas pipeline failures.

The EUB is the government agency that facilitates hearings and makes decisions regarding the suitability of resource development projects. If polled, the general public would probably want the Board to be cautious in terms of the actions taken to reduce risk rather than just being cautious in estimating the risk. The adoption of fixed reference risk criteria would enable transparency in the risk decision process and would allow the comparison of projects or facilities.

10.0 Interpretation of significance

10.1 Applicable Risk Criteria and Comparisons

Canada's Major Industrial Accident Coordinating Committee (MIACC) published in 1991 the Land Use Planning and Control Annual Report (MIACC, 1991) which included a pictograph of allowable land uses from their Risk Acceptability Criteria. Although MIACC has subsequently been dissolved (December 1999) their allowable land uses criteria continues to be used by some jurisdictions. The MIACC Risk Acceptability Criteria are presented in Table 10.1 and detail annual individual risk estimates.

Currently, in Alberta, there are different regulatory bodies governing the location of developments: municipal boards, planning commissions, the Department of Environment and for the oil and gas industry the EUB. The location of wells and other oil and gas collection, processing and transmission facilities are determined by "setbacks" as established by the EUB. These setback distances are detailed in Table 10.2. (AEUB, 2000).

Table 10.1 – MIACC Risk Acceptability Criteria

Allowable Land Uses	Annual Individual Risk
Risk Source	
No other land use (setback)	
Manufacturing, warehouses, open spaces (parkland, golf courses etc.)	100 in a million ($1x10^{-4}$)
Commercial, offices, low density residential	10 in a million ($1x10^{-5}$)
All other uses including: institutions high density residential	1 in a million ($1x10^{-6}$)

Table 10.2 - AEUB Setback Distances (AEUB, 2000)

Level of Sour Facility (Well, pipeline or plant)	Volume of H_2S Released	Minimum Setback Distances
1	$< 300m^3$	100m (except for pipelines which have a right of way setback -municipal by-law)
2	$300m^3 \leq$ volume $\leq 2000m^3$	100m Individual dwellings Unrestricted county development 500m Urban centre or public facility
3	$2000m^3 \leq$volume $\leq 6000m^3$	100m Individual dwelling 500m Unrestricted county development 1500m Urban centre or public facility
4	$> 6000m^3$	As specified by the AEUB but not less than level 3

The definitions of the terms used in Table 10.2 are (AEUB, 2000):

- Individual dwelling - permanently occupied by a resident.
- Unrestricted county development -dwellings situated outside an urban centre and having more than eight permanent dwellings per quarter section.
- Urban centre - a city, town, new town, village, summer village or hamlet with not less than 50 separate buildings.
- Public facility - a public building such as a hospital, rural school or a major recreational facility and includes any other development that the EUB may designate as a public facility based on the complexity of evacuation (campground).

In addition to establishing setback distances within which the facility construction must occur, the EUB also requires the calculation of a hazard distance which corresponds to the emergency planning evacuation zone (calculation - CPA, 1987).

Table 10.3 details the release volumes, the EUB hazard level and the calculated annual individual risk values for the two pipeline cases assessed.

Table 10.3 - Release Volumes, EUB Hazard Level and Annual Individual Risk

% H_2S	**Maximum Distance to a concentration of 100ppm***	**Distance to a maximum 1% probability of Lethality* (m)**	**H_2S release volume (m^3)***	**EUB Hazard level**	**Calculated Annual Individual Risk of Fatality PD=1% P(exp)=1.0****	**Calculated Annual Individual Risk of Fatality PD=1% P(exp)= $1<x\leq 0.1$****
2.5	543	107	140	1	9.3 x10^{-8}	1.1 x10^{-11}
	652	159	190	1	1.4 x10^{-7}	1.6 x10^{-11}
	813	229	360	2	2.0 x10^{-7}	2.3 x10^{-11}
	957	307	670	2	2.7 x10^{-7}	3.1 x10^{-11}
	1090	363	1300	2	3.2 x10^{-7}	3.6 x10^{-11}
	1200	390	2590	3	3.4 x10^{-7}	3.9 x10^{-11}
30	2000	641	2540	3	5.6 x10^{-7}	6.6 x10^{-11}
	2650	935	3550	3	8.2 x10^{-7}	9.6 x10^{-11}
	3670	1600	7140	4	1.4 x10^{-6}	1.7 x10^{-10}
	4360	2200	13500	4	1.9 x10^{-6}	2.3 x10^{-10}
	4830	2610	26900	4	2.3 x10^{-6}	2.7 x10^{-10}
	5130	2880	53600	4	2.5 x10^{-6}	3.0 x10^{-10}

*Distance and volumes values have been rounded to 3 significant figures.
**Risk values have been rounded to 2 significant figures.

In the all of the cases presented the nearest allowable resident to a sour facility is in an individual dwelling located at a distance of 100m from the pipeline, and in all of the cases the distance to a maximum concentration of 100ppm is greater than 100m, in some cases considerably greater. (100m is the closest setback distance.) For all of the Level 2 cases presented the distance to a maximum concentration of 100ppm exceeds a distance of 500m, the prescribed minimum separation between a level 2 facility and an urban centre or public facility. For the

Level 3 and 4 facilities the distances to a maximum concentration of 100ppm (for all but the 2.5% H_2S 20000m segment) greatly exceed the minimum setback of 1500m prescribed for an urban facility or public centre.

Initially the setback distances may appear inadequate however, they must be considered in conjunction with the risk associated with the facilities. Land developers are lobbying for a relaxation in the setback distances while some landowners are lobbying for increased distances. The criteria for the development of the setback distances is not available in the public domain, therefore the setback distances were identified for re-examination by the Alberta Provincial Advisory Committee on Public Safety and Sour Gas (Provincial Advisory Committee on Public Safety and Sour Gas, 2000).

As indicated in Table 10.3 the dispersion or plume of H_2S resulting from a failure of a sour gas pipeline can extend, in a worst case but realistic scenario, a distance of a number of kilometers. The extent of the plume dispersion and dilution is directly related to the concentration of the original source the wind speed and the meteorological conditions. At a "low" wind speed of 2 meters/second a plume could cover the setback distance of 100 meters in less than a minute. While exclusion zones of several kilometers are not proposed as alternatives to the existing distances, specific factors must be considered when developing setbacks. The factors for consideration include:

- age of the pipeline;
- diameter of the pipeline;
- proposed preventative maintenance operations;

- ESD valve spacing;
- population density and spatial distribution around the pipeline right-of-way;
- compliance history of the pipeline operator;
- proposed or existing land use and land zoning classification; and
- proposed efficiency of the emergency notification and evacuation procedure.

In a comparison of the data in Table 10.3 with the MIACC criteria (Table 10.1) there is a moratorium on land development proposed at levels of annual individual risk greater than 100 in a million (> 1.0×10^{-4}). Development immediately adjacent to the right of way for some of the 2.5% H_2S pipeline scenarios examined would satisfy the MIACC criteria. Regardless of its falling within the MIACC criteria, development adjacent to sour gas pipeline right-of-ways would be expected to meet with public opposition.

10.2 What is acceptable as a level of risk?

While scientists and engineers can calculate risk levels based on probabilities and frequencies, and in many cases provide defensible scientific rationale and some evidence for their estimates, ultimately it is society that must determine which risks are acceptable and which are not. Scientific analysis can yield only the estimates of risk; there is no scientific equation that governs acceptability. The determination of acceptable risk is problem specific and requires the choice between alternatives (Fischcoff et al., 1981). The choices are dependent on values, beliefs, and experience and are unique to each individual (Angle, 1983). Each problem must be solved independently but within the existing matrix of risk issues.

There can be no single number that will define acceptable risk across distinct and different societies (Fischhoff et al., 1981).

What is acceptable will also depend on its presentation and whether the risk is voluntary or involuntary (Atallah, 1980). Smoking, a voluntary activity albeit confounded by the addictive properties of nicotine, carries a potential risk of lung cancer of approximately 17% among lifetime male smokers in Canada (Villeneuve and Mao, 1994). This risk is one for which a large body of scientific and statistical evidence exists. Smoking however is a risk widely accepted by a significant proportion of the population. The percentage of Canadian males who smoked as detailed in the 2001 National Population Health Survey was 23.5% (Statistics Canada, 2002b). This percentage equates to 3.6 million male smokers (Statistics Canada, 2000), if 17% of them develop lung cancer that is approximately 610,000 cases of lung cancer that are being accepted by the male population of Canada.

Living next to a nuclear power plant or a hazardous waste plant may be involuntary depending on when the facility is sited. While the perceived risk may be high the estimated risk is substantially lower than the smoking risk. Any risk associated with living next to a nuclear power or hazardous waste plant is unacceptable to a significant proportion of the population. This lack of acceptance of the risk associated with industrial or perceived higher risk facilities arises from the apparent absence of any benefit contrasted with the imposed risk, no matter how small (Atallah, 1980). Risks undertaken voluntarily are much more readily accepted than involuntary risks, or those risks that exists because of the decisions or activities of others (i.e. siting of industrial facilities).

Often risk estimates are offered to the public to provide reassurance when the public is being asked to assume involuntary risk. In situations where an event is calculated to have a low annual individual risk of fatality (e.g. nuclear reactor accidents, failure of hazardous waste landfills) these events may also be rare occurrences. The low risk may have more uncertainty associated with it (Finkel, 1990) than a comparatively higher risk activity (i.e. smoking) because the lower risk is estimated based on rare events. Risks from rare events may be are calculated from a complex array of assumptions or models, rather than a direct cause and effect relationship like smoking. There is true variability in the failure rate when the expected rate is determined primarily from frequency data (Rowe, 1994). If however there is minimal failure data because the process is new or rare, there will also be a large degree of uncertainty in the estimates because of lack of knowledge issues.

The debate surrounding acceptable risk raises the conundrum of how risk estimates should be presented. Should a low-level risk be described in a reassuring way, yet not guaranteeing absolute safety, or should "usual" personal behavior be modified if a regulatory standard of risk is exceeded (Goldstein et al, 1992)? In public health situations where the target is usually to limit the lifetime individual risk level to less than 1 in 100,000 or 1 in a million ($1x10^{-5}$ or $1x10^{-6}$), there exists an unacknowledged sense of consensus that government action to protect public health is appropriate. For example the World Health Organization (WHO) water quality guidelines for carcinogens are based on an individual lifetime cancer risk of

1 in 100,000 (1×10^{-5}), which equates to an annual individual risk of 1.4×10^{-7} (based on a lifetime of 70 years)).

The reference level of risk for a lifetime individual risk is proposed to be within the range of 1 in 100,000 and 1 in a million (1×10^{-5} and 1×10^{-6}) (Hattis, 1996). This range enables distinct societies to recognize their own uniqueness within a scientifically defensible reference risk level. The risks in question are those that cannot be modified by individual behaviors, avoided, or those risks that are acts of God or nature over which no one has control (Goldstein et al., 1992). A lifetime individual risk of 1 in a million (1×10^{-6}) equates to an annual individual risk of 1 in 70 million or 1.4×10^{-8}.

If, for the purpose of comparison, a lifetime risk criteria is established as 1 in a million (1×10^{-6}), there is a need to identify risks which have the same magnitude, and which are also involuntary. Goldstein et al. (1992) have proposed three criteria for the comparison of low-level risks:

1) the risk is at a level low enough that it does not cause the individual concern during the activities of daily life;
2) it is possible to prevent exposure to the actual events which precede the risk by adjusting daily routines, however the risk is perceived as so low as to not warrant such preventative actions; and
3) no personal benefit is derived, or specific detriment suffered, from the source of the risk.

The risk of fatality associated with a pipeline failure meets the three criteria proposed above. The risk is an involuntary risk to individual citizens, regardless of the magnitude of the risk and it is a low-level risk even for those in closest proximity to the source. Two other risk scenarios are proposed that also meet the stated criterion and are also involuntary and low-level risks:

1) the individual risk of fatality to an individual on the ground because of an airplane accident; and
2) the individual risk of fatality from a meteorite or asteroid colliding with the Earth.

The individual lifetime risk of fatality from an airplane accident while being on the ground has been estimated as an average value of 4.2×10^{-6} for the entire population (Goldstein et al., 1992). Thompson et al. (2001) further examined the groundling fatality data and proposed a decreasing risk grid as detailed in Table 10.4. (The Thompson et al. (2001) analysis did not include the fatalities associated with the terrorist attack on the World Trade Centre.)

Table 10.4 - Risk to Groundlings from Airplane Accidents

Location	**Annual Individual Risk**	**Lifetime Individual Risk (70 years)**
End of the runway	1×10^{-4}	7.0×10^{-3}
Within 0.2 miles of a city airport	$> 1\times10^{-6}$	$>7.0\times10^{-5}$
General population	1.3×10^{-8}	9.1×10^{-7}

The risk of fatality associated with airplane accidents is so low that people do not change their daily routines to avoid airports or flight paths. While avoiding areas of increased air traffic would reduce the risk, it is perceived as being so low that avoidance is not necessary (Goldstein et al., 1992). Some individuals may avoid purchasing homes near an airport, but this is more likely driven by the avoidance of nuisance aircraft noise than by any perception of fatality risks from airplane accidents. There is a great deal of both variability and uncertainty in the risk estimates. The variability originates from the frequency data associated with the different types of airports and airplanes, and the uncertainty is due to the fact that while airplane accidents do cause ground fatalities they are rare events (Thompson et al., 2001).

The lifetime risk fatality associated with a collision between Earth and an asteroid or meteorite has been estimated as at least equal to or greater than that from airplane crashes (Lewis, 1996). Although apparently beyond human control, there might be preventative actions possible if the problem was fully understood. A global-billion killer is a celestial body with a size range of between several hundred meters and a kilometer, this impactor will threaten life on a global scale and could cause the destruction of human civilization or extinction of the human species. Every 70 thousand to 1 million years a global-billion-casualty killer will strike. It is estimated that a one-thousand-gigaton impact (the critical explosive power to cause worldwide effects) occurs almost once every million years; that is a risk of 1×10^{-6} of worldwide devastation (Lewis, 1996).

The meteorite and asteroid risk estimates have contributions of both uncertainty (the mere quantity of unknowns and potential contributors to the collision) and variability (the analysis of the existing frequency data) (Giogini et al., 2002). The nature of both the variability and the uncertainty are detailed in Giogini et al.'s (2002) analysis of the 2880 encounter between asteroid 1950Da and Earth. The fatality risk associated with a collision between Earth and another celestial body is at a low level such that the three criteria detailed are met. Daily life is in no way altered in order to avoid the possibility of a fatality due to an impact on the Earth, however should an impact be imminent individuals may consider preventative action.

The risk of fatality from a pipeline release is also a low-level risk that the majority of individuals do not alter their daily routines in order to avoid the risk. The risk may be perceived to be so low that avoidance of pipelines is not deemed to be necessary to avoid the risks associated with their rupture. Individuals may also be taking the risk unknowingly, through their daily commuting patterns.

The similarities between the risk of fatality from a pipeline failure and the risk of groundling fatality from an airplane accident extend beyond their low-level and their "involuntaryness". The decreasing risk profile with distance from an airport for the groundling fatality risk is similar to the contaminant plume from a pipeline rupture. The contaminant plume is most concentrated at source and the concentration decreases as the distance from the source increases. The risk associated with exposure to the contaminant is also highest closest to the source and decreases with increasing distance from it; the similar risk estimates for the airplane accidents are detailed in Table 10.4.

10.3 Precautionary principle

In 1992 the Rio Declaration (of the United Nations) proclaimed the Precautionary Principle stating that "In order to protect the environment, the precautionary approach shall be widely applied by States according to their abilities.

Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." (United Nations, 1992). The effects of greenhouse gas emissions on global warming, and the ratification or dismissal of the Kyoto accord by countries in the developed and developing world, is an example where the invocation of the Precautionary Principle by the United Nations may be viewed as an attempt to take an effective first step in slowing the pace of global climate change (Leiss, 2001). The Precautionary Principle has been utilized by stakeholders to include the prevention of threats to human health (Hrudey, 2000).

In instances where there is a belief that there exists a threat of serious or irreversible environmental or public health damage, the Precautionary Principle may be invoked. This enables the cessation of activities which may cause serious harm, but for which the data detailing absolute scientific certainty does not exist. The argument and submissions of some affected stakeholders during hearings for the siting of critical sour gas wells have implied the invoking of the Precautionary Principle; without addressing the principle by name.

The risks associated with an action or activity need to be assessed and the risk management actions (those actions put into place to mitigate or reduce the risk) need to be appropriate. While there may be a certainty that pipelines will leak and that combinations of H_2S concentration and time can produce serious effects in the exposed population, the risk management actions need to provide an identifiable and quantifiable risk reduction in their application.

In instances of very rare events, those events with low frequencies (like a pipeline failure), it can be demonstrated that even for very good diagnostic tools (leak detection systems) the majority of responses by the system will be false positives and the non-response will be predominantly for true negatives. A false positive will occur when the leak detection equipment detects a leak and no leak actually exists, and a false negative occurs when a leak exists but the leak detection equipment does not detect it. Hrudey and Leiss (2003) presented the contrast of reality and screening data in the form of a 2x2 logic table; Table 10.5. The Hrudey and Leiss (2003) logic table was modified to apply directly to the pipeline failure scenario.

Table 10.5 - 2x2 Logic Table for Pipeline Failures

REALITY

EVIDENCE	Condition exists **Pipeline leak**	Condition does not exist **No pipeline leak**
Screening or diagnostic test is positive **Leak detection is positive**	Correct result (True Positive) **(TP)**	False Positive **(FP)** (Type 1 error)
Screening or diagnostic test is negative **Leak detection is negative**	False Negative **(FN)** (Type 2 error)	Correct result **(TN)** (True Negative)

The positive predictive value (PPV) is the probability that given a positive screening result, the condition truly does exist. The negative predictive value (NPV) is the probability that given a negative screening result, the condition truly does not exist.

$$\text{PPV} = \left(\frac{TP}{TP+FP}\right) \qquad \text{and} \qquad \text{NPV} = \left(\frac{TN}{TN+FN}\right)$$

The PPV must be distinguished from the Sensitivity of the detection of the condition (leak) which is a measure of the capacity of the leak detection device to respond to true leaks. Sensitivity is the probability of obtaining positive evidence given that the condition being screened exists.

The sensitivity is $\mathrm{Se} = \left(\frac{TP}{TP + FN} \right)$

Likewise, the NPV is different from the Specificity of the detection of the condition (leak). Specificity is the probability of obtaining negative evidence; given that the condition being screened for is absent.

The specificity is $\mathrm{Sp} = \left(\frac{TN}{TN + FP} \right)$

The frequency of a condition is the measure of its actual occurrence.

For the pipeline failure case:

- PPV = the probability that given a positive leak detection result; there is a leak.
- NPV = the probability that given a negative leak detection result; there is no leak.
- Se = the probability that given the occurrence of a leak; a leak will be detected.
- Sp = the probability that given that there is no leak; no leak will be detected.

In the case of pipeline failures a frequency of 100% would mean that every pipeline failed within the time frame of analysis (i.e. once per year for every kilometer would be 100% for typical pipeline statistics). From the previously detailed statistics in Section 7.2 the expected number of pipeline failures in the next year is 19 in 15135 km of sour service pipeline, for a frequency statistic of $1.3\text{x}10^{-3}$; this is a low frequency. The true failure frequency statistic is plotted as 0.13% on Figures 10.1, 10.2 and 10.3.

In order to complete the logic table the sensitivity and the specificity of the screening tool need to be specified. A type I error (α) is the false positive rate, the chance of allowing a false positive, and its occurrence is determined from (1- sensitivity). A type II (β) error is the false negative rate, the chance of allowing a false negative, determined from (1- specificity). Scientific convention sets α = 5% and β =20% for hypothetical testing of experimental evidence (Hrudey and Leiss, 2003). For the purpose of this study it has been assumed that the hypothetical screening tool is exceptional and has a false positive rate of 1% (α=1%, sensitivity = 99%) and a false negative rate of 2% (β=2%, specificity = 98%). The effect of different values of α and β on the PPV and the NPV is illustrated in Table 10.6. In Figure 10.1 the PPV (the probability that a leak detected is a true leak) is plotted as a function of the failure frequency. The plot shows that the PPV drops in direct proportion to the failure frequency. For the pipeline failure frequency statistic (0.13%) the PPV is 6%(5.9%). In Figure 10.2 the NPV (the probability that no detection means no leak) is plotted as a function of the failure frequency and for decreasing failure frequency, the NPV approaches 100%. For the pipeline failure frequency statistic (0.13%) the NPV was essentially 100% (99.9987%). These statistics mean that 5.9% of the time when a leak is detected it is a true leak and 99.9987% of the time when no leak is detected there is no leak occurring.

Table 10.6 - Effect of Different Type I and Type II errors on PPV and NPV *

Type I and Type II errors	PPV	NPV	Chance of a false negative response (1-NPV)
α=1%, β=2%	6%	100% (99.9987%)	1.3 x10^{-3}%
α=10%, β=15%	0.7%	100% (99.9852%)	1.5 x10^{-2}%

*for a pipeline failure frequency of 0.13% (0.0013)

Table 10.6 illustrates that by increasing the Type I error level (false positive rate) from 1% to 10% the PPV (the probability that a leak detected is a true leak) decreases from 6% to 0.7%. By increasing the Type II error level (false negative rate) from 2% to 15% the NPV (the probability that no detection means no leak) does not substantially change. In pipeline failure situations a type I error is substantially more desirable than a type II error where the consequences may be devastating.

This analysis reveals the problem of diminishing returns. If pipeline leaks are relatively rare events then increased monitoring may initially serve to identify additional leaks, but at the point of diminishing returns no additional quantity of detection will identify additional leaks. The failure to detect a leak when one has occurred is (1-NPV). As indicated in Figure 10.3 the chance of experiencing a false negative response (i.e a failure to detect a leak when one has occurred) is very low in cases where the event frequency is low. The failure statistic for potential pipeline failures is indicated on the figure and at a failure rate of 0.13 % the chance of a false negative is 0.0013%.

The analysis illustrates that it is the failure frequency rate rather than the effectiveness of the screening tool that determined the chance of a false negative response of the failure that is the failure to detect a leak when one exists.

Figure 10.1 - Frequency of Failure vs PPV
Sensitivity =99%, Specificity =98%

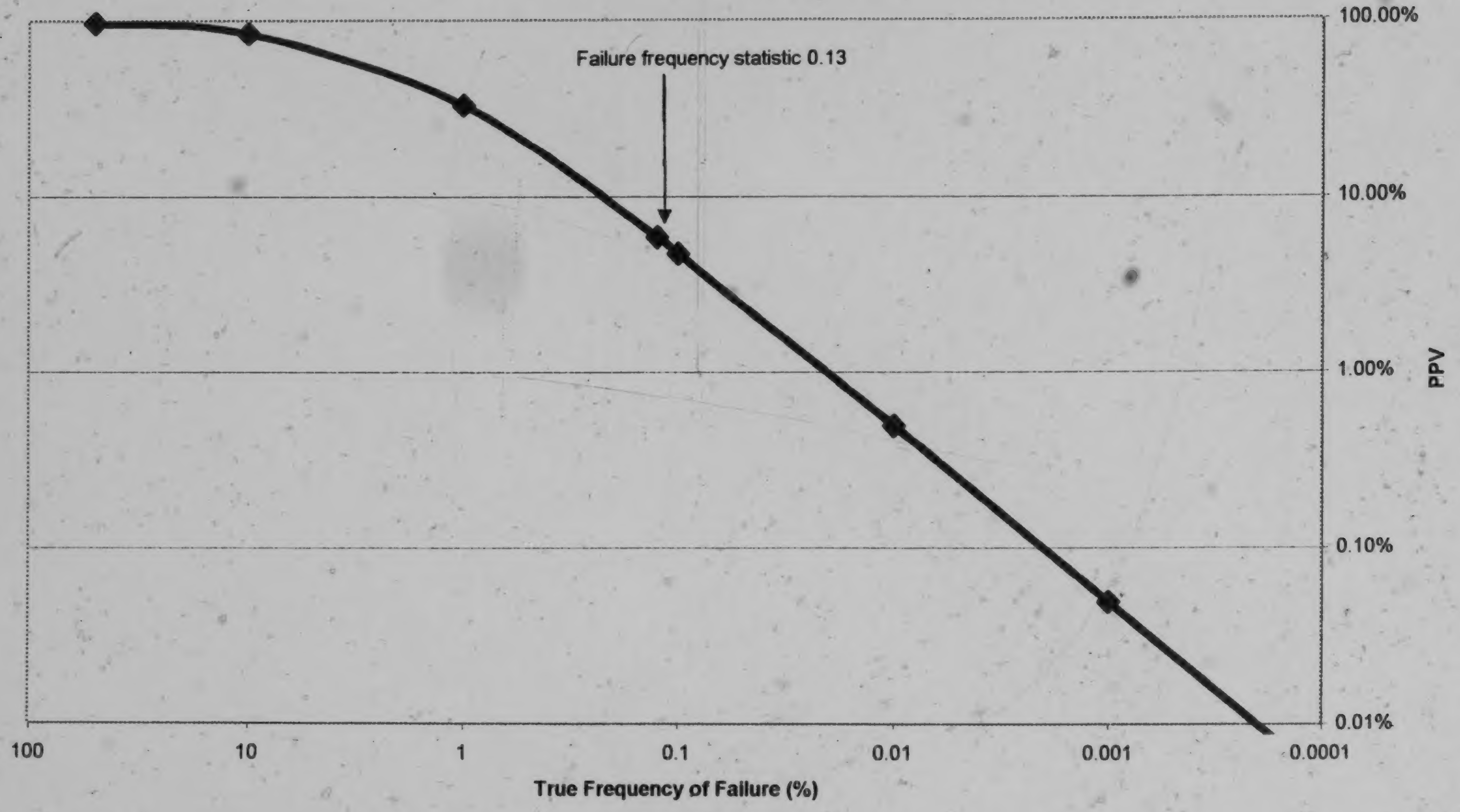


Figure 10.2 - Failure Frequency vs NPV
Sensitivity =99%, Specificity =98%

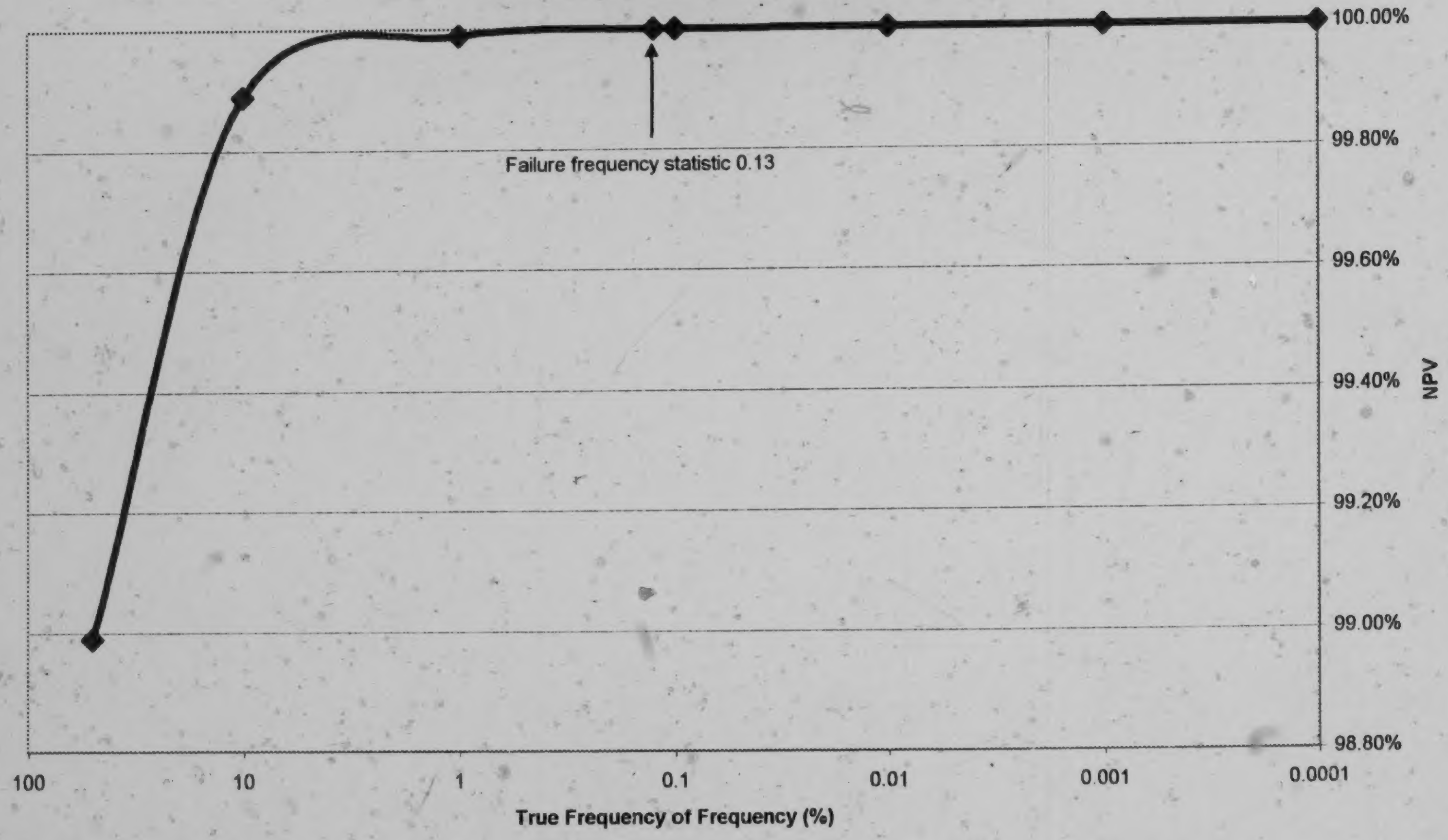
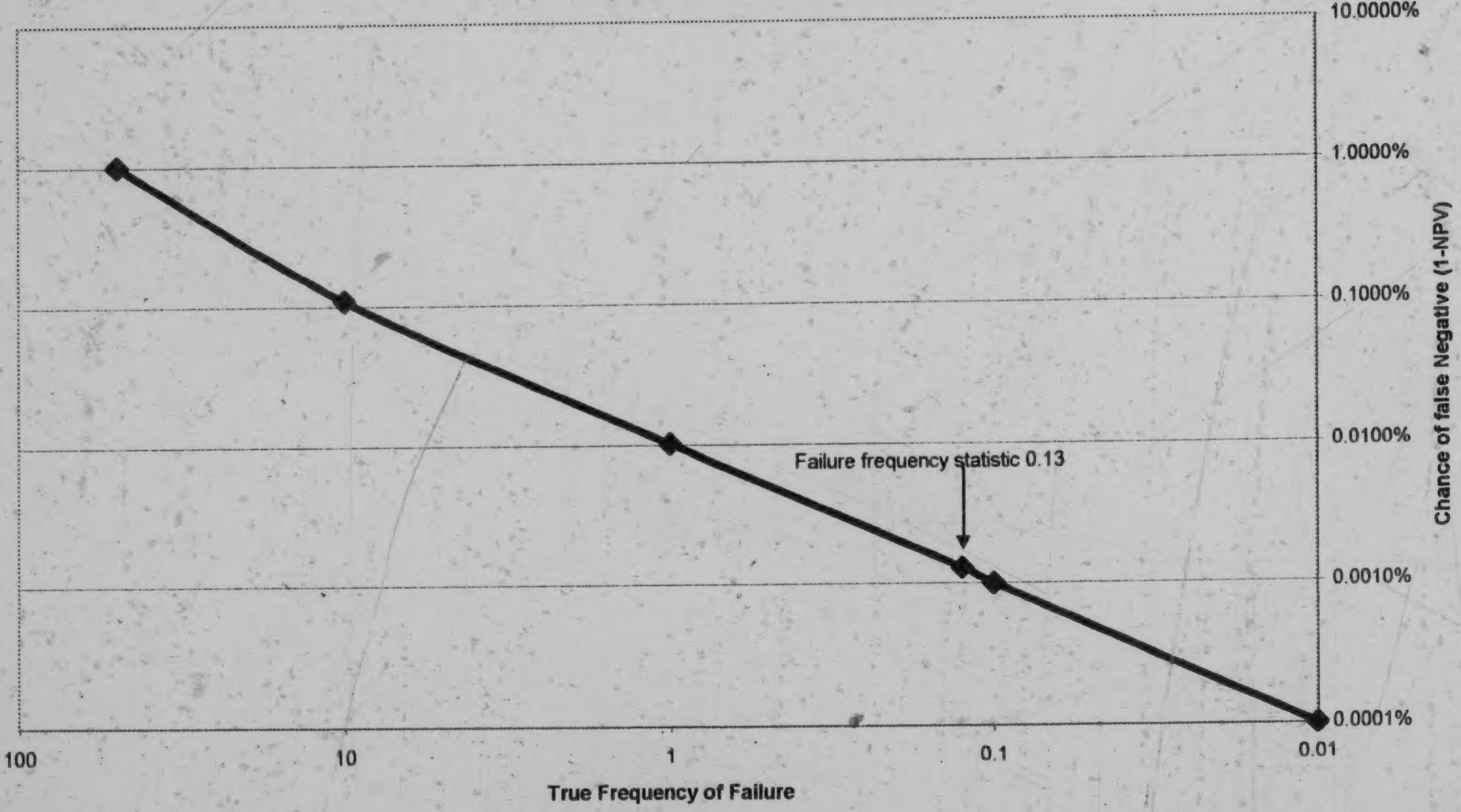


Figure 10.3 - Failure Frequency vs Chance of a False Negative
Sensitivity =99%, Specificity =98%



10.4 Societal acceptance of pipeline risk

In 2001 the research firm Ipsos-Reid was retained by the Canadian Energy Pipeline Association (CEPA) to conduct surveys in order to obtain an independent assessment of the level of knowledge and the attitudes of four stakeholder groups regarding the Canada's pipeline industry. The stakeholder groups were: landowners along the routes of the pipeline, adjacent landowners (those in close proximity to a pipeline), the general population, and the news media. CEPA's findings included "a higher than expected level of knowledge and a generally positive attitude towards the energy industry" (CEPA, 2001). CEPA represents 11 oil and gas transportation companies (including ATCO, NOVA, Enbridge, Transmountain) and the majority of the product shipped is sweet product (less than 4ppm H_2S). Can society's apparent acceptance of sweet product transmission be translated to an equal level of acceptance of sour product transmission? While high pressure gas lines have a unique set of risks there appears to be a tacit acceptance of their existence by society and therefore an acceptance of the risk that accompanies them. The gas lines crossing under 23rd Ave in Edmonton beneath the new South Edmonton Common, and the pipelines running through residential developments in Cochrane speak to a tacit (but not necessarily fully informed) acceptance of the risk. Is the risk of a pipeline failure of a high volume, high-pressure gas line substantially less than a sour gas line?

The societal acceptance or lack of acceptance of gas pipelines appears to be directly related to the hydrogen sulphide present in the pipelines and the known public health effects associated with exposure. Is H_2S exposure much more harmful to the receptor population than high-pressure gas? In the CEPA survey 62% of the landowners agreed that the pipeline company "provides appropriate compensation to me for the use of my land" (CEPA, 2001). This statement implies that landowners are paid on an on-going basis for the use of their land for the location of the transmission lines after the initial land disturbance has occurred; a land rental fee. On-going compensation does not occur in the Alberta oil-patch for land used for product transmission; an initial crop loss fee is paid for the disturbance associated with the construction of the pipeline, but annual land rentals are not the norm. On-going annual compensation to the landowner does occur for loss of revenue (crop-loss) associated with the existence of a well site or oil battery location.

11.0 Environmental Risk Management principles

Hattis (1996) proposes a framework for the scrutiny of risk management alternatives primarily for the examination of decision criteria for regulatory actions and the analysis of numerical risk estimates as they bear relevance to environmental policy. Hattis (1996) suggested that a major impetus of risk control is public outrage over unfair imposition of risks on particular people, for the benefit of others. The guiding values or ethical principles were expanded by Hrudey (2000) to included a comprehensive set of guidelines to be utilized in concert with each other (not one or another in isolation) in order to effectively guide the comparison of available risk management alternatives.

Ethical Principles to Guide Risk Management (Hrudey (2000) after Hattis (1996))

1. **Do more good than harm** - The first principle is based on the Hippocratic Oath for physicians - Do no harm. This reflects a realization and admission that there are no zero risk alternatives in any situation and that risk management decisions invariably include tradeoffs among competing risks. The decision-maker should carefully consider and seek to be confident that the proposed risk control methods will overall do more good than harm.
2. **Fair process decision making** - As identified by Hattis (1996) public outrage over unfair imposition of risks on some people for the benefit of others is the underlying issue in many risk controversies. Hrudey (2000) also details that a perceived lack of fairness underlies the majority of risk disputes. A fair process, or natural justice, requires that the affected parties are given input to the decision, that is appropriate for their stake in the outcome. In order to have

public consent there must appear to be a sense of equity, and individuals must be able to avoid specific risks that they deem to be unreasonable compared to the benefits that they offer (Hattis, 1996, Hrudey, 2000). A sense of natural justice is paramount to the democratic process (Hrudey, 2000). Risks that are fully disclosed and judged to be reasonable may be assumed voluntarily. Disclosure of the risk management steps to manage the non-zero risks fulfils the obligation to communicate risk information accurately (Nakayachi, 1998). It is not enough to be informed of the decision there must have been a fair and reasonable opportunity to determine the decision.

3. **Insure an equitable distribution of risk** - The principle of equality is an underlying premise of our society, highlighted by a total lack of tolerance for any appearance of discrimination or prejudice. Risk management must balance the risks and benefits to affected individuals in an effort to establish equity associated with the situation (Hrudey, 2000). The assumption of most of the health risk by farmers on whose land a sour gas development will occur does not appear to be fair when the development company in Calgary bears much less health risk, and concurrently assumes all profit and most benefit from the venture. The people of Alberta, in general, benefit from the royalty payments and economic spinoffs. The practice of a cash payout for use of the land has developed although these transactions have not been explicitly negotiated on the basis of risk. In the case of the farmer who receives a large sum of money from the oil company for the development of a sour gas well on his property, there is a sense of inequality or lack of equity if there is no benefit to the surrounding

landowners. The surrounding landowners also assume risk with the development and often do not experience direct benefit. Developing companies inject money into the community through sponsorship of local sports or activities, but the benefits are substantially less tangible. (This lack of equity is an underlying factor in many risk controversies regarding resource development.)

4. **Seek optimal use of limited risk management resources** - The most optimal use of limited resources must be sought in order to achieve the highest level of effective risk management for the dollars spent. There is a finite supply of risk management expertise and additional funds injected into a project will not increase that intellectual pool. The intellectual and technical resources must be allocated to deal with the problems where the greatest result can be achieved. This optimization of resources can be considered to be utility (Hrudey, 2000). Hattis (1996) suggested two questions: 1) Are the most important hazards the targets of risk mitigation efforts?; and 2) Considering the options available, do the risk management programs represent the very best possible use of skills and resources? The optimal use of risk management resources may be different in the reduction of individual risk rather than population or societal risk. A hazard that has an individual lifetime risk of 1×10^{-6} may be considered acceptable for an individual, however the same hazard may be considered unacceptable, and require mitigation, in a different location owing to the surrounding population density (Goldstein et al., 1992). Thus population risk and individual risk are considered differently in the management of risk management resources.

5. **Promise no more risk management than can be delivered** - Honesty is considered a core value in our society for good reason. Dishonesty undermines the function of a civil society. Nakayachi (1998) studied public reaction in situations where it was indicated that zero risk was impossible, but where the risk management options were outlined in detail; the results suggested that public confidence did not wane, rather that corporate honesty in such cases was valued. When unrealistic expectations are created for risk management that cannot then be achieved, avoidable conflict is generated (Hrudey, 2000). The risk estimates presented must reflect the level of certainty in the result. Ignoring uncertainty or not recognizing the limitations of models or assumptions, introduces a greater chance of making a bad decision; an uniformed decision is the result if uncertainty is ignored. An uniformed decision impairs the ability to use the risk estimates as a decision making tool. Overconfidence in risk assessment causes problems in risk management and risk communication (Hrudey, 2000).
6. **Impose no more risk than you would tolerate yourself** - or "Do unto others as you would have done to you" inherently includes the concepts of not causing harm, fairness, honesty, best use of resources, and not making promises that cannot be kept. This last guideline grounds all of the concepts on a personal level that should cause a decision-maker to have appropriate second thoughts.

12.0 *Discussion*

The objective in completing the pipeline risk assessment was to identify those issues which create public concerns and misunderstandings at the time of project development and then serve to cause knowledge disparity or an emotional rift between industry and the public. Resource development in the Province of Alberta is encroaching on populated areas, economics and depletion of sweet oil and gas reserves is the impetus behind the development of reservoirs of sour oil and gas.

The Government recognized the public concerns regarding the development of sour gas resources, and in January 2000 the Provincial Advisory Committee on Public Safety and Sour Gas was established. The efforts of this committee followed on the heels of the efforts of the 1994 Advisory Committee to the ERCB, Reviewing Public Safety and Sour Gas. The principal areas of concern, identified by the 2000 Provincial Advisory Committee on Public Safety and Sour Gas, regarding sour gas development, production and pipeline transportation centred around:

- the lack of knowledge regarding the health effects of sour gas at low levels for long term or chronic exposures;
- the required setbacks for sour gas development; and
- the implications of sour gas development on public safety.

The hypothetical, generic risk assessment completed on the pipeline in central Alberta identified the three consequence endpoints by which risks can be quantified. These are:

- Concentration (100ppm concentration detected as a maximum in a 3 or 30 minute meteorological averaging period). This endpoint reaches the greatest distance from the pipeline rupture and consequently is the most stringent for industry. This distance is not considered a setback distance, rather it could be a basis for public safety planning. The 100ppm-concentration endpoint generates the greatest hazard zone distance (in the majority of cases); fatalities are not expected to occur at the outer boundaries of the concentration consequence endpoint.

- Equivalent dose (exposure to 100ppm endpoint for 30 minutes). This endpoint boundary is located between the concentration and lethality endpoints. The equivalent toxic load, calculated using the Triple Shifted Rijnmond (TSR) equation, yields an exposure of $3.0\text{x}10^{6}\text{ppm}^{2.5}$minute. The hazard distances generated through use of this criterion provide a protective basis for public safety planning because fatalities are not expected to occur at this distance from the source. The equivalent dose (100ppm for 30 minutes) is the evacuation standard for Alberta Health and the EUB.
- Lethality (probability of lethality of 1% as calculated using the TSR probit equation). A 1% probability of fatality (TSR) equates to a toxic load of $13.0\text{x}10^{6}\text{ppm}^{2.5}$minute. At the hazard distance corresponding to the lethality consequence endpoint the exposure criterion represents the maximum distance or boundary at which the predicted fatality estimates could be as high as 1%. This hazard distance is located in closest proximity to the pipeline and is the least stringent for the developer.

The three endpoints are distinctly different in their proximity to the pipeline and have different public safety implications. At none of the three endpoints identified is a catastrophe expected to occur. All three of the endpoints are expected to provide a cautious level of protection from a pipeline failure. Table 12.1 illustrates the difference in distance between the point where a catastrophe is expected to occur (PD50%) and the three studied endpoints. The data presented are for a 30% H_2S pipeline with a segment length of 5000m. The PD50% is estimated, through the use of the Triple Shifted Rijnmond equation, to occur at 210m from the rupture, a distance considerably closer to the rupture site than any of the other endpoints.

Table 12.1 Endpoints on the exposure continuum

Exposure Endpoint	Distance from rupture (m)
Concentration (100ppm)	4360
Dosage (100ppm for 30minutes)	2820
Probability of Lethality PD1% (TSR)	2200
Probability of Lethality PD50% (TSR)	210

The EUB have developed a calculation nomograph for the determination of hazard distance. The EUB hazard distance is not a setback, rather it is used for recommending the Emergency Planning Zone (EPZ), which is the notification and evacuation zone in the case of an emergency. The EPZ distance, which is either the dosage or the concentration endpoint depending on whether the release is from a well or a facility, is defined by the EUB as a hazard distance, one not based on risk. The release is simply assumed to have occurred therefore the accident is assumed to have occurred, probability and frequency information for the accident are not considered (RWDI, 2000).

In the majority of cases the EUB hazard distance is the most stringent hazard distance, located further from the pipeline than the concentration consequence endpoint. For H_2S release volumes of less than $275m^3$ the EUB hazard distance is less than the concentration endpoint hazard distance. While the concentration endpoint distance is great enough that no fatalities are expected to occur at the distance, the cross-over in the EUB and the 100ppm curve raises questions as to the level of caution used in the setting of the nomograph.

Producers who believe that the EUB EPZ hazard distances are too great can apply for a reduction to the hazard zone based on situation specific circumstances (AEUB, 2001). For release volumes of less than 275m^3 the EUB hazard distance is not the most protective.

The implications of EPZ hazard zone size for industry are directly financial. The larger the EPZ hazard zone the greater are the resources required to manage the zone. The producer has direct responsibility for managing access to and egress from the EPZ and contacting and evacuating all individuals located within the zone, if required. This entails investing in emergency response planning such that effective evacuation of the EPZ would be achieved.

The EUB hazard and risk analysis protocols are currently being developed (AEUB, 2002). The Hazard protocol relates directly to the calculation of the EPZ while the Risk protocol relates more to the different consequence endpoints and their implications to public safety and planning. The hazard protocol underwent industry review in mid-2002 and is currently undergoing revisions, the risk protocol has been delayed in the short-term in order that Alberta Health and Wellness can study the different consequence endpoints; particularly the equivalent toxic load endpoint.

The EUB appears to consider hazard and risk as two entirely different concepts, associated with different distances from the facility, pipeline or well. The two concepts cannot be separated completely. In order to be at risk, a hazard must exist; the hazard is the component of a risk with the potential to cause harm and the hazards associated with H_2S are not disputed. The EPZ distance is essentially a dynamic setback distance that is invoked in response to an incident.

Pipeline failures are rare events, thus the failure frequency is very low. Failures do happen, therefore it is necessary to attempt to identify the level of risk associated with pipeline failures and to interpret both what the risk really means and how the risk estimate is calculated. Some common misconceptions exist about the contaminant plume, specifically regarding its make-up and movement.

When a pipeline fails the release is a transient process that typically lasts from several minutes up to an hour, depending on the volume of gas released and the meteorological conditions. The plume is dynamic and the contaminant concentration changes over the duration of time and distance. The plume is a mixture of both H_2S and natural gas and is a heterogeneous mixture that is most concentrated along the centre line and most dilute along the plume boundary edges. The H_2S and natural gas are fully mixed in the pipeline and upon rupture the contaminant plume remains that way. The impression that the sour gas can separate from the plume and concentrate in the low-lying areas under the contaminant plume but remote from the source is erroneous. Natural gas mixtures containing low levels of H_2S ($<7\%$) will generally be buoyant at expanded atmospheric conditions. However, during rapid depressurization from high pressure conditions to atmospheric conditions, the rapid cooling and the formation of small amounts of liquid aerosols can contribute to an initial negative buoyancy near the release source (<500m). Denser gases may be neutrally or negatively buoyant after their release and may travel at ground level or undergo dense gas slumping effects in the near release area prior to becoming buoyant at expanded atmospheric conditions (Dowsett, 2003). Therefore due to gravity slumping there may be amounts of dense gas in low-lying areas in the immediate release area.

The belief that the plume has a constant homogeneous concentration, which moves as a block, is erroneous. The plume is most concentrated at source and has a dynamic make-up. As the plume grows the exterior edges of the plume become less concentrated as ambient air is entrained into the plume. As the distance of the plume grows the quantity of the plume diluted by the entrained air increases. When a plume develops from an elevated stack it takes the shape of a three dimensional cone. The horizontal cross-sectional area of the plume is therefore a triangle; the plume originating from a pipeline rupture is not initially elevated (the release occurs at ground level) thus while the plume takes the shape of a cone on its upper border the lower border is limited by ground level. The cross-sectional shape generated at ground level, where the potential receptors exist, is an oval. This oval shape may be counterintuitive but it exists because of the tilting of the plume upwards from ground level; thus there is an angled cone which is intersected by a level plane. Because the pipeline failure is a transient process where the quantity of contaminant released into the atmosphere is distinct, the release process is short-term. Consequently, there is an end to the plume.

The development of the risk estimate for fatality from exposure to a pipeline release is based upon:

- frequency estimates for pipeline failures and meteorological conditions;
- assumptions of geometry and release scenarios and receptor populations; and
- calculation of probability of fatality from the TSR probit equation, and exposure and interaction length as derived from the fatality calculations.

The dispersion model is the determinant of the distance to the toxic load correlated with a maximum probability of fatality of 1%. SLAB is the dispersion model favoured and endorsed by the EUB (AEUB, 2002). There is some uncertainty in the dispersion model, however it has been validated using actual release data.

There is considerable uncertainty in the TSR toxic load model. There are a number of toxic load models. The TSR equation is utilized by the EUB and was utilized in the calculation of dose and exposure in this risk assessment. Some of the other toxic load models that exist were discussed in the text. The equations each present varying data points for each toxic load. The AEGL-3, that has been proposed by the US EPA, appears to be a case of favouring stricter regulations based on worst case assumptions because of the level of uncertainty.

The uncertainty associated with the calculation of the toxic load corresponding to a toxic load equivalent to a probability of fatality of 1%, is the greatest contributor to uncertainty in the risk estimate. In order to accurately determine the hazard distance associated with a probability of fatality of 1%, the toxic load model must be determined with greater certainty. The toxicology of low-level acute exposure to H_2S needs to be more accurately determined. While there is no question regarding the effects of high level acute H_2S exposure, the human data are not the result of controlled experiments. This has resulted in the actual levels causing fatalities being calculated retrospectively by inference. The evidence available for doing such retrospective exposure assessments is often weak. As the toxic load equation relies on many historical animal experiments, the results should be revisited, the equation re-evaluated and the experimental work redone using physiologically based pharmacokinetic (PBPK) models to validate their results from animals to humans. The existing models may not represent physiological reality at either low concentrations or split-second exposure times.

In Canada, there is no established Tolerable Daily Intake (TDI) for H_2S; the US EPA values currently form the basis of the accepted LOAEL and NOAEL values.

Risk estimates are calculated assuming a continuous receptor population available on a 24 hour a day basis. In order to calculate risk estimates that can be comparable to other estimates for other risks this assumption is necessary. The assumption however causes an increase in the cautiousness of the risk estimate; individuals examining the risk estimate may not understand the cautious nature of the assumptions that have been made. An example calculation illustrated the difference in the orders of magnitude of the risk estimates when the receptor locations were included in the risk estimate. With specific behavior patterns factored into the risk estimate the risk declined by two orders of magnitude.

With any individual risk estimate there will be a wide range of possible values, reflecting the wide range in individual habits and vulnerability to harm

(HSE, 1989). Thus any specific individual may have a risk estimate that is higher or lower than the calculated value. This range of values is represented by the Monte Carlo analysis of the data. In the Monte Carlo analysis the data are represented as distributions, either frequency distributions for variable terms or probability distributions for uncertain terms. These distributions are an alternative to point estimates. The Monte Carlo analysis generates a distribution for the risk estimate. In completing a Monte Carlo analysis the data points are considered as distributions; the distributions are user-defined thus the assumptions made by the user are also subject to uncertainty. A sensitivity analysis, that is made possible by Monte Carlo simulation, allowed for the distinguishing of the effects of variability from the effects of uncertainty in the inputs and determination of the principal contributors to the uncertainty in the risk estimate (Burmaster et al, 1994). In the risk assessment completed the toxic load calculation (an uncertainty term) was by far the greatest contributor to the uncertainty in the risk estimate.

When risk estimates associated with sour gas pipelines or facilities are presented at open houses or public forums, there is a perception that "There is a risk" means "I am at risk". There is a difference between risk to a specific individual and risk to any member of the exposed population. The risk to any random member of the exposed population, assuming a constant receptor for exposure, is significantly higher than the risk to a specific individual. The general risk estimate is reduced through the consideration of exposure patterns and location specific details. There will still be concern within the population that anyone is at risk, even if it is understood that the specific individual is not a member of the immediate family.

However, the pragmatism of individuals is more likely to be evident when dealing with any hypothetical individual, rather than someone known to the person.

While there is a risk of exposure, as pipeline failures do occur, the risk is low for the general population. This difference was illustrated using examples of known hazards (avalanches, automobile accidents and the West Nile virus) and this must be effectively communicated to the general public. Individuals who live in closest proximity to a pipeline obviously have the highest risk of exposure during a pipeline failure.

For the general population the individual risk of fatality from the rupture of a sour gas pipeline is comparable to the risk of fatality from an airplane accident for anyone on the ground. Thompson et al (2001) calculated the risk isopleths associated with being a groundling fatality, those risk levels are similar to the risk estimates generated in the risk assessment associated with fatality from a pipeline rupture.

All individuals take risks in the performance of daily life (driving to work, crossing the street, driving by an airport) and some people participate in higher risk activities voluntarily (smoking, parachuting, rock climbing). These higher risk levels are deemed to be acceptable by individuals as the activities are undertaken voluntarily and personal benefit is derived from them. Generally a lower level of risk (or greater level of safety) is demanded when there is an involuntary exposure to a hazard resulting from the activities of others, particularly when a direct or immediate individual benefit is not realized from the activities (Atallah, 1980). In order to compare the risk associated with fatality from a pipeline rupture other involuntary, yet unavoidable, low level risk scenarios were identified (asteroid or meteorite collision with the Earth and being a groundling fatality as a result of an airplane accident).

The 1×10^{-6} lifetime individual risk level was adopted as a reference risk level for the purposes of discussion in this paper. The comparison of the risk of fatality from a pipeline failure to other low-level risks served to indicate that the risk level was such that, for comparable risk levels, individuals did not alter their daily behavior and that the risk level was not recognized to be unacceptable.

FN (frequency and fatality) curves were presented as a depiction of societal risk levels for the risk assessment performed. FN curves become asymptotic at the limit of population density (i.e. the number of fatalities from an event remains the same regardless of the frequency of the event because all of the available population has become fatalities). FN curves relate only to fatalities and do not allow for other aspects such as economic losses, however the FN curve data clearly illustrate how increasing the setback distance or decreasing the spacing between ESD valves serves to reduce the risk associated with the pipeline. The calculated FN curves do not illustrate the impact on society of different sizes of accidents with the same overall number of fatalities (HSE, 1989).

The calculated risk estimate, as generated through the use of the Monte Carlo analysis, illustrates both the range of values of the risk estimate and the level of uncertainty in the result. As identified in the ethical principles to guide risk management, no more risk management should be promised than can be delivered. For risk estimates where there is a significant degree of uncertainty (as illustrated by the range of risk values calculated) the limitations to our knowledge make risk management decisions more difficult, but it is dishonest to claim confidence that we do not possess (Hrudey, 2000).

Risk management, done well, is precautionary in its nature, because it is preventive rather than reactive (Hrudey and Leiss, 2003). The application of the precautionary principle to environmental and health hazards is in the distillation of the uncertainty in the information, available through the determination of false positives and false negatives from screening data (Hrudey and Leiss, 2003). The determination of a true pipeline failure is likely because false negative responses are rarer than the failure frequency. The dilemma arising is the appropriate use of resources in the management of rare hazards (the majority of environmental hazards are rare) as additional resources can be allocated in the effort to detect every one of the rare hazards, however a point of diminishing returns will be encountered.

The use of the ethical principles proposed by Hrudey (2000) and Hattis (1996) to guide risk management decisions will not eliminate all controversy or dissent in the public forum, rather a fair basis for decision making can be proposed. These guidelines make the decision making process more difficult, but should make the decision better for the rule of law in a civil society. Effective communication, and an effort to distill the differences in presented risk estimates from any individual to a specific individual, may aid in the elimination of some misunderstanding. Credible action by regulatory agencies to reduce substantially any of the sources of uncertainty (i.e. toxic load models) will give further credence to the risk estimates generated for discussion.

13.0 Conclusions

Pipeline failures will continue to occur in the Province of Alberta precipitating a clear need for effective management and communication of health risks that may arise from such failures. The following conclusions are drawn from the evaluation of questions of interpretation that arose in preparing and explaining the risk assessment performed on a hypothetical, but realistic, sour gas pipeline scenario in Alberta.

1. Representing and communicating the risk of pipeline ruptures and their potential health risks as accurately as possible is expected to achieve greater understanding of the risk issue by the general public than risk estimates that are artificially inflated by overly cautious assumptions. Ensuring that the actual risk management measures are adequately cautious should be more important and effective than simply over-estimating expected risks to appear to be cautious. The latter may only serve to create misunderstanding and apprehension because the overly cautious risk estimates may appear high enough to cause concern for some.

2. Assessing whether risk management measures are adequately cautious requires that risk estimates are based on calculations and technical assumptions that are defensible under close scrutiny. These risk estimates then need to be compared with published, and consistently applied, risk criteria to demonstrate that the risk management measures imposed are capable of achieving the required risk criteria. Cautionary risk estimation will only lead to cautionary action if compared to some reference.

3. There have been no fatalities in the general public associated with acute exposure to H_2S from a pipeline rupture in Alberta. Thus, the EUB risk reduction measures, as attained through their mandated setback distances and operating protocols, have so far proven successful in assuring public safety; this despite the inevitability of pipeline failures. Tangible risk management measures imposed to reduce risk levels need to be clearly identified and better described regarding the risk reduction they achieve. The success of the current or any newly imposed risk reduction measures needs to be effectively communicated.

4. Other involuntary risks with comparable or higher risk levels to those caused by sour gas pipelines (e.g. groundling fatality from airplane accidents or death as a result of a collision between Earth and another celestial body) have not caused our society to implement specific actions or behaviour modifications specific to risk avoidance.

5. The risk to any random individual from the general population located at the lethality (PD1%) endpoint distance during a release is higher than the risk to a specific individual in the general public for a pipeline rupture scenario. The difference between these risks can be orders of magnitude. The exposure assumption used in current risk assessments for the EUB is that there is always an unlucky member of the general population at the endpoint distance; thus there is a constant exposure. This difference, between "there is a risk" and "I am at risk", must be more effectively communicated to stakeholders in the risk management process. The reasons for the risk difference should be explained in order for a more personalized understanding of the risk estimate by the affected individuals.

6. The risks of fatality from a sour gas pipeline are difficult to convey. Although there is a level of certainty that a pipeline failures will occur in Alberta, the potential exposed population is unknown. The uncertainty of the potential for exposure compounds the miscomprehension of the actual risk level.

7. The level of integration and iteration required to generate the risk assessment data and the risk profile curves is too complex to be completed by hand. A member of the public interested in calculating their own individual specific risk level would not be likely to be able to reproduce a risk value estimated by others. Because transparency is a core requirement for effective risk assessment, this complexity and the reliance of the assessment process on technical assumptions is a major challenge to the credibility of the process.

8. The EUB should establish and publish achievable and expected risk targets (clearly defined in terms of risk characteristics, i.e. any individual and/or societal risk) to be achieved by wells, pipelines and facilities. Detailing an explicit risk target will enable operators to address the risk issue with data indicating how the reference risk levels have been achieved and potentially bettered.

9. A better understanding of the acute toxicity of H_2S and the toxic load concept is necessary to reduce the uncertainty in health risk estimates associated with pipeline failures. The Triple Shifted Rijnmond (TSR) probit equation is used to determine the proportion of the population affected by a specified toxic load. This equation, the first principles from which it was derived and the methodology behind each of the two shifts and final selection of the triple shifted criterion need to be re-explained in a position paper by the EUB to facilitate a greater understanding of the

application of toxic load by risk managers who seek to apply the TSR equation to sour gas release data.

10. Any of the three endpoints identified (concentration, equivalent concentration / dosage, or maximum of a 1% probability of lethality) could be used by the EUB in the establishment of emergency planning zones (EPZ) or setbacks. None of the distance endpoints were associated with the realistic expectation of any fatalities despite the implicit logic inferred by the (maximum) 1% probability of lethality criterion.

11. The difference in hazard distances for differing endpoints illustrates the importance of the endpoint selection for public safety management and land-use. All of the endpoints occur on the same exposure continuum. A more explicit effort should be made to distinguish a point of extreme catastrophe (e.g. realistic likelihood of 50% fatality) from the other endpoints where no fatality is truly expected.

12. The EUB has been successful in limiting the risk to the public from sour gas, i.e. they have been successful in managing the risk. The public issues surrounding sour gas health risk have apparently been less successfully managed by the EUB. Risk issue management may require less effort for the siting and the operation of sour gas facilities if the public had a greater degree of confidence in the risk reduction measures undertaken.

13. The use of the ethical principles proposed by Hrudey (2000) and Hattis (1996) to guide risk management decisions will not eliminate controversy or dissent in the public forum, but they can offer guidance for insuring the fairest

possible basis for decision-making. These guiding principles should be observed as far as possible within the mandate of the decision-making process.

14. Problems arise in the comprehension of risk because at face value the risk estimate appears to be a simple concept. This simplicity is deceptive as many assumptions and qualifiers are included and inferred in the risk estimation process. This necessary intuition results in a process that is unlikely to be understood by all involved.

15. The subtleties of various risk criteria (specific individual, any random individual or total population risk) are neither well understood nor well explained in current practice. Better understanding of these subtleties should allow for more effective risk issues management, if not more effective risk management.

14.0 References

Advisory Committee to the ERCB, Reviewing Public Safety and Sour Gas. 1994. Public Safety and Sour Gas. Appendix C - Technical Information.

Alberta Energy and Utilities Board (AEUB). 1997. Interim Directive ID 1997-06. Sour well licensing and drilling requirements.

Alberta Energy and Utilities Board (AEUB). 1998. Report 98-G. Pipeline performance in Alberta 1980-1997.

Alberta Energy and Utilities Board (AEUB). 2000. Guide 56. Energy Development Application Guide. Volume 2. Appendix 3.

Alberta Energy and Utilities Board (AEUB). 2001. Interim Directive ID 2001-05. Public safety and sour gas policy recommendations 54, 60 and 61, Site-specific emergency response plans for sour operations, emergency planning zones and reduced planning zones.

Alberta Energy and Utilities Board (AEUB). 2002. Draft Protocol for Hazard and Risk Analysis of Sour Gas Developments.

Alberta Environment. 2000. Alberta Ambient Air Quality Guidelines. Environmental Protection and Enhancement Act. February, 2000.

Alberta Health and Wellness. 2002. Health effects associated with short-term exposure to low levels of hydrogen sulphide (H_2S) - A technical review

Alberta Health and Wellness. 2003. Personal communication. Karina Bodo.

Alberta Health. 1988. Report on H_2S Toxicity.(65 pages)

Alberta Human Resources and Employment. 1998. Workplace Health and Safety - Hydrogen Sulphide. CH029 July 1998.

Angle RP. 1983. Risk analysis and sour gas. Paper presented at the 1983 Annual Meeting Canadian Western Regional (Alberta) Chapter Pacific Northwest International Section Air Pollution Control Association. June 28, 1983. Calgary Alberta.

Angle RP and Sakiyama SK. 1991. Plume Dispersion in Alberta. Standards and Approvals Division, Alberta Environment, Edmonton, Alberta. 428pp.

Arulanandam SJ, Wilson DJ, Hrudey SE. 1997. Gas pipeline failures: Analysing the data. *Proceedings Risk Based Priorities for Managing Environmental Issues for the Oil and Gas Industry*. Air and Waste Management Association. April 1997.
Atallah S. 1980. Assessing and managing industrial risk. *Chemical Engineering*. September 8, 1980. 94-103

Bercha Group. 2002. Progress Report #1 - Determination of sour gas well and pipeline failure frequencies. (unpublished)

Bogen KT. 1995. Methods to approximate joint uncertainty and variability in risk. *Risk Analysis*. 15(3): 411-419

Brenneman KA, James RA, Gross EA, Dorman DC. 2000. Olfactory neuron loss in adult male CD rats following subchronic inhalation exposure to hydrogen sulfide. *Toxicologic Pathology* 28: 326-333

Burmaster DE, Anderson, PD. 1994. Principles of good practice for the use of Monte Carlo techniques in human health and ecological risk assessments. *Risk Analysis*. 14(4): 477-481.

Cairns T. 1980. The ED01 Study: Introduction, objectives and experimental design. *Journal of Environmental Pathology and Toxicology*. 3(3):1-7.

Canadian Energy Pipeline Association (CEPA). 2001. Stakeholder Research Study - Summary.

Canadian Petroleum Association (CPA). 1987. CPA Guidelines for preparation of sour gas emergency response plans for sour gas and oil facilities.

CCPS. 1989. Guidelines for Chemical Process Quantitative Risk Analysis. Centre for Chemical Process Safety of the American Institute of Chemical Engineers.

Concord Environmental Corporation. 1993. Risk Analysis of Sour Gas Facilities. Appendix C: Technical information. Report and recommendations to the ERCB on public safety and sour gas. Advisory Committee to the ERCB, Reviewing public safety and sour gas.

Cullen AC, Frey HC. 1999. Probabilistic Techniques in Exposure Assessment - A handbook for dealing with variability and uncertainty in models and inputs. Plenum Press. New York. USA

Dorman DC, Brenneman KA, Struve MF. 1999. Experimental investigations into the neurotoxicity and nasal toxicity of hydrogen sulfide in rats. *Environmental Epidemiology and Toxicology*. 1:249-255.

Dorman DC, Kimbell JS. 2002. Nasal toxicity of hydrogen sulfide in rats and significance for human risk assessment. *CIIT Activities*. 22(3-4) March-April 2002: 1-10.

Dowsett I. (RWDI West Inc.) 2002. Personal communication. May 16, 2002.

Dowsett I. (RWDI West Inc.) 2003. Personal communication. March 29,2003.

Drummond I, House F, McMullen WG, Stewart JA. 1996. Hydrocarbon gases and hydrogen sulphide: A code of practice. *Applied Occupational and Environmental Hygiene*. 11(5): 493-500

Energy Resources and Conservation Board (ERCB). 1990. Report 90-B. Volume 6. Risk Approach - An Approach for Estimating Risk to Public Safety from Uncontrolled Sour Gas Releases. Concord Environmental. October 1990.

Environment Canada. 1996. Meteorological Data for Edmonton International Airport 1992-1996.

Finkel AM. 1990. Confronting Uncertainty in Risk Management. A Guide for Decision-Makers. Center for Risk Management Resources for the Future. Washington. DC.

Finley B, Proctor D, Scott P, Harrington N, Paustenbach D, Price P. 1994. Recommended distributions for exposure factors frequently used in health risk assessment. *Risk Analysis*. 14(4): 533-553.

Finney DJ. 1971. Probit Analysis. Cambridge University Press. 3rd edition.

Fischoff B, Lichtenstein S, Slovic P, Derby SL, Keeney RL. 1981. Acceptable Risk. Cambridge University Press. Cambridge, UK

Frey HC. 1992. Quantitative analysis of uncertainty and variability in environmental policy making. Report. American Association for the Advancement of Science. Exposure Assessment Group, Office of Health and Environmental Assessment.

Giorgini JD, Ostro SJ, Benner AM, Chodas PW, Chesley SR, Hudson RS, Nolan MC, Klemola AR, Standish EM, Jurgens RF, Rose R, Chamberlin AB, Yeomans DK, Margot J.-L. 2002. Asteroid 1950DA's encounter with Earth in 2880: physical limits of collision probability prediction. *Science*. Volume 296: 132-136.

Goldstein BD, Demak M, Northridge M, Wartenberg D. 1992. Risk to groundlings of death due to airplane accidents: a risk communication tool. *Risk Analysis*. 12(3): 339-341.

Gordis L. 2000. Epidemiology. (Second Edition). W. B. Saunders Company. Philadelphia, Pennsylvania, USA.

Guidotti TL. 1994. Occupational exposure to hydrogen sulphide in the sour gas industry: some unresolved issues. *International Archives of Occupational and Environmental Health.* 66:153-160

Guidotti TL. 2002. As cited in the Edmonton Journal. December 3, 2002. Study clears low-dose sour gas but skeptics warn facts sparse. A7.

Guo B. 2001. Biological Variability in Risk Assessment Modeling of Industrial Gases. M.Sc. Thesis. Department of Public Health Sciences.University of Alberta.

Haines A. 2002. As cited in the Edmonton Journal. October 14, 2002. A new way to look at pipelines. C4

Hattis D. 1996. Drawing the line - Quantitative criteria for Risk Management. *Environment*. 38(6): 12-15 and 35-39

Health and Safety Executive (HSE). 1992. Risk Criteria for land-use planning in the vicinity of major industrial hazards. Her Majesty's Stationary Office. London. UK.

Hilderman T, Wilson D. 2000. Hydrogen sulphide toxic load fatality model. Unpublished technical note.

Hilderman TL, Wilson DJ, Hrudey SE. 2000. Application of inter- and intra-species uncertainty factors to rat fatality data used in the hydrogen sulfide AEGL-3 levels. Presented at the API Hydrogen Sulfide Health Research and Risk Assessment Symposium. Chapel Hill, NC, USA

Hrudey SE. 2000. Class Notes. PHS 512. University of Alberta.

Hrudey SE, Leiss W. 2003. Risk management and precaution: Insights on the cautious use of evidence. *Environmental Health Perspectives.* Published online June 11, 2003. doi:10.1289/ehp.6224. in press.

Johnson BB, Slovic P. 1995. Presenting uncertainty in health risk assessment: initial studies of its effect on risk perception and trust. *Risk Analysis.* 15(4): 485-494

Kaplan S, Garrick BJ. 1981. On the quantitative definition of risk. *Risk Analysis.* 1(1): 11-27

Kates RW. 1978. Risk Assessment of Environmental Hazard. SCOPE. Report 8. Chichester Wiley. (As referenced in Angle 1983).

Klaassen CD (editor). 2001. Casarett and Doull's Toxicology: The Basic Science of Poisons. 6th Edition. McGraw-Hill Companies Inc. New York, USA

Layton DW, Cederwall RT. (1987). Predicting and managing the health risks of sour gas wells. *Journal of the Air Pollution Control Association*. 37:1185-1190

Leiss W. 2001. In the Chamber of Risks: Understanding Risk Controversies. McGill - Queens University Press. Montreal, Canada

Lewis JS. 1996. Rain of Iron and Ice - The very real threat of comet and asteroid bombardment. Helix Books. Reading, Massachusetts, USA.

Lewis RJ (editor). 1992. Sax's Dangerous Properties of Industrial Materials. Eighth edition. Van Nostrand Reinhold. New York. USA.

Major Industrial Accident Coordinating Committee (MIACC). 1991. The Land Use Planning and Control Annual Report.

Meek ME, Long. 1996. Health -Based Tolerable Daily Intakes/Concentrations and Tumorigenic Doses/Concentrations for Priority Substances. Health Canada. Ottawa, Canada. As cited in Thomas and Hrudey, 1997.

Moore WJ. 1972. Physical Chemistry. Fourth Edition. Prentice-Hall International Inc. London, UK.

Nagy GZ. 1991. The odour impact model. *Journal of the Air and Waste Management Association*. October 1991, 41(10): 1360-1362.

Nakayachi K. 1998. How do people evaluate risk reduction when they are told zero risk is impossible? *Risk Analysis*. 18(3). 235-242.

Neilson G. (AEUB) 2002. Personal communication. July 8, 2002.

NIOSH. 1996. Hydrogen Sufide - (IDLH) Immediate danger to life or health documentation. Technical Report. National Institute of Occupational Health.

Ontario Ministry of the Environment (OME). 1989. The role of the odour impact model in standard setting in Ontario. Paper presented at the 36th Ontario Waste Management conference, 13 June 1989. Toronto. Ontario.

Pasquill F. 1960. The estimation of dispersion of windborne material. *Meteorological Magazine*. 90: 33-49

Petroleum Communication Foundation (PCF). 2000. Sour Gas: Questions and Answers. (36 pages)

Provincial Advisory Committee on Public Safety and Sour Gas. 2000. Public Safety and Sour Gas. Findings and Recommendations Final Report.

Rijnmond Public Authority. 1982. Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, A pilot study. Report to the Rijnmond Public Authority. D Reidel Publishing Company. Dordrecht, Holland. Appendix VII The Cremer and Werner Report.

Rogers RE. 1990. Toxicological Justification of the Triple Shifted Rijnmond Equation. Technical Report. Alberta Energy Resources and Conservation Board (ERCB). 1990. Appendix B, Volume 7. Report 90-B Risk Approach: An Approach for estimating risk to public safety from uncontrolled sour gas releases.

Rowe WD. 1994. Understanding Uncertainty. *Risk Analysis*. 14(5): 743-750

RWDI West Inc. 2000. An Evaluation of Emergency Planning Zone Criteria Applied in Alberta. Submitted to the Alberta Energy and Utilities Board.

Shusterman D. 1992. Critical review: the health significance of environmental odor pollution. *Archives of Environmental Health*. 47: 76-87

Statistics Canada. 2002a. CanSim II table 051-0001. Post-census estimate.

Statistics Canada. 2002b. CanSimII table 105-0027. National Population Health Survey - Year 2001.

Statistics Canada. 2000. Population of Canada. Post-census estimate.

Thomas SP, Hrudey SE. 1997. Risk of Death in Canada - What we know and how we know it. University of Alberta Press. Edmonton. Alberta.

Thompson KM, Rabouw RF, Cooke RM. 2001. The risk of groundling fatalites from unintentional airplane crashes. *Risk Analysis*. 21(6): 1025-1037

United Nations. 1992. Rio Declaration on Environment and Development. U.N. Doc./Conf.151/5/Rev.1. New York.

United States Environmental Protection Agency (EPA). 1987. Integrated Risk Information System (IRIS) - Hydrogen sulphide (CASRN 7783-06-4)

United States Environmental Protection Agency (EPA). 1999. Risk Management Program Guidance for Offsite Consequence Analysis

United States Environmental Protection Agency Office of Pollution Prevention and Toxics (EPA). 2000. Hydrogen Sulfide CAS Reg. No. 7783-06-4. Proposed Acute Exposure Guideline Levels (AEGLS). Public Draft.

United States Environmental Protection Agency (EPA). 2002. Toxicological review of hydrogen sulfide (and IRIS summary) external review draft.

Villeneuve PJ, Mao Y. 1994. Lifetime probability of developing lung cancer, by smoking status, Canada. *Canadian Journal of Public Health*. 85(6). 385-388. As cited in Thomas and Hrudey, 1997.

Wilson DJ. 2002. Personal communication. June 2, 2002

Appendix 1 – Peng Robinson Equation of State

Peng Robinson Equation of State

$$P = \frac{RT}{V-b} - \frac{a\alpha}{V^2 + 2bV - b^2}$$

R = Ideal gas constant (8.31451 J/mol°K)

$$a = \frac{0.45724 R^2 T_c^2}{P_c}$$

$$b = \frac{0.07780 R T_c}{P_c}$$

$$\alpha = \left(1 + \left(0.37464 + 1.54226\omega - 0.26992\omega^2\right)\left(1 - T_r^{0.5}\right)\right)^2$$

$$T_r = \frac{T}{T_c}$$

where ω = the accentric factor for the species

http://www.wikipedia.org/wiki/Equations_of _State

Pratt R.M. 2001. Thermodynamic Properties Involving Derivatives using the Peng –Robinson equation of state. *Chemical Engineering Education*. Spring 2001. Volume 35(2).

Appendix 2 – Risk Profile Spreadsheets

Risk in an oval plume

Input Data

Frequency of hazard (pipeline break)	7.45E-04 failures/km*year
Maximum hazard distance (distance to PD 1%)	0.107 kilometers
Plume dispersion angle	15 degrees
Assumed lethality at source	100 percent
Calibration to existing regulatory policy	1 (1.0 or other factor)

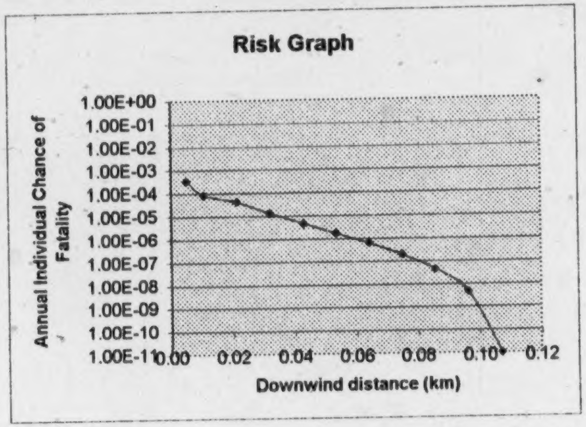
Pipeline data (descriptive only- NOT data inputs)

H2S concentration	2.5 %
Segment length	500 m
Volume of gas released	142 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.05	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.21	1.00000	0.95	0.9533	2.2004	7.45E-04	1.00	3.34E-04
1	0.01	0.10	15.00	5.35E-03	7.04E-04	0.02	1.18E-05	0.21	0.47469	0.90	0.4272	1.2472	7.45E-04	1.00	8.45E-05
2	0.02	0.20	15.00	1.07E-02	1.41E-03	0.05	4.74E-05	0.21	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	4.47E-05
3	0.03	0.30	15.00	1.61E-02	2.11E-03	0.07	1.07E-04	0.20	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	1.31E-05
4	0.04	0.40	15.00	2.14E-02	2.82E-03	0.10	1.89E-04	0.20	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	4.72E-06
5	0.05	0.50	15.00	2.68E-02	3.52E-03	0.12	2.96E-04	0.19	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	1.77E-06
6	0.06	0.60	15.00	3.21E-02	4.23E-03	0.14	4.26E-04	0.17	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	6.28E-07
7	0.07	0.70	15.00	3.75E-02	4.93E-03	0.17	5.80E-04	0.15	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	1.92E-07
8	0.09	0.80	15.00	4.28E-02	5.63E-03	0.19	7.58E-04	0.13	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	4.30E-08
9	0.10	0.90	15.00	4.82E-02	6.34E-03	0.22	9.59E-04	0.09	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	4.48E-09
10	0.11	1.00	15.00	5.35E-02	7.04E-03	0.24	1.18E-03	0.03	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	1.07E-11
											2.2004				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	3.34E-04
0.01	8.45E-05
0.02	4.47E-05
0.03	1.31E-05
0.04	4.72E-06
0.05	1.77E-06
0.06	6.28E-07
0.07	1.92E-07
0.09	4.30E-08
0.10	4.48E-09
0.11	1.07E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 0.159 kilometers

Plume dispersion angle 15 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 2.5 %

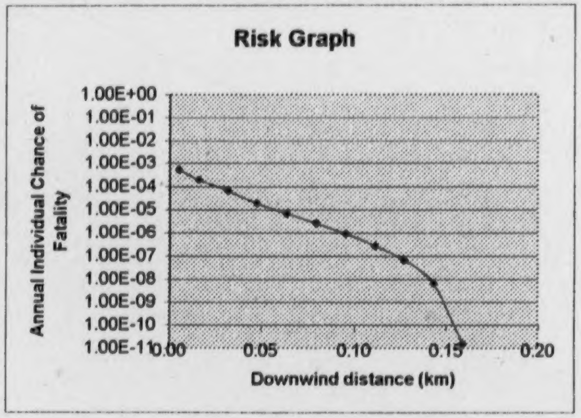
Segment length 1000 m

Volume of gas released 191 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.03	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.32	1.00000	0.97	0.9686	2.4022	7.45E-04	1.00	5.51E-04
1	0.02	0.10	15.00	7.95E-03	1.05E-03	0.04	2.61E-05	0.32	0.68189	0.90	0.6137	1.4336	7.45E-04	1.00	2.07E-04
2	0.03	0.20	15.00	1.59E-02	2.09E-03	0.07	1.05E-04	0.31	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	6.64E-05
3	0.05	0.30	15.00	2.39E-02	3.14E-03	0.11	2.35E-04	0.30	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	1.95E-05
4	0.06	0.40	15.00	3.18E-02	4.19E-03	0.14	4.18E-04	0.29	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	7.01E-06
5	0.08	0.50	15.00	3.98E-02	5.23E-03	0.18	6.54E-04	0.28	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	2.63E-06
6	0.10	0.60	15.00	4.77E-02	6.28E-03	0.21	9.41E-04	0.25	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	9.33E-07
7	0.11	0.70	15.00	5.57E-02	7.33E-03	0.25	1.28E-03	0.23	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	2.86E-07
8	0.13	0.80	15.00	6.36E-02	8.37E-03	0.29	1.67E-03	0.19	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	6.40E-08
9	0.14	0.90	15.00	7.16E-02	9.42E-03	0.32	2.12E-03	0.14	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	6.65E-09
10	0.16	1.00	15.00	7.95E-02	1.05E-02	0.36	2.61E-03	0.04	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	1.58E-11
											2.4022				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	5.51E-04
0.02	2.07E-04
0.03	6.64E-05
0.05	1.95E-05
0.06	7.01E-06
0.08	2.63E-06
0.10	9.33E-07
0.11	2.86E-07
0.13	6.40E-08
0.14	6.65E-09
0.16	1.58E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break)	7.45E-04	failures/km*year
Maximum hazard distance (distance to PD 1%)	0.229	kilometers
Plume dispersion angle	15	degrees
Assumed lethality at source	100	percent
Calibration to existing regulatory policy	1	(1.0 or other factor)

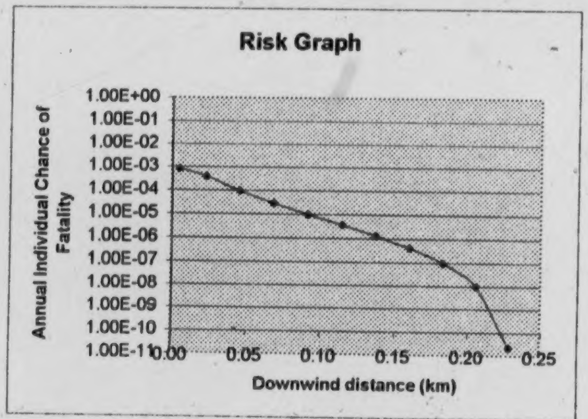
Pipeline data (descriptive only- NOT data inputs)

H2S concentration	2.5	%
Segment length	2500	m
Volume of gas released	364	(m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.02	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.46	1.00000	0.98	0.9782	2.5531	7.45E-04	1.00	8.52E-04
1	0.02	0.10	15.00	1.15E-02	1.51E-03	0.05	5.42E-05	0.46	0.83885	0.90	0.7550	1.5749	7.45E-04	1.00	4.04E-04
2	0.05	0.20	15.00	2.29E-02	3.01E-03	0.10	2.17E-04	0.45	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	9.56E-05
3	0.07	0.30	15.00	3.44E-02	4.52E-03	0.15	4.88E-04	0.44	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	2.81E-05
4	0.09	0.40	15.00	4.58E-02	6.03E-03	0.21	8.68E-04	0.42	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	1.01E-05
5	0.11	0.50	15.00	5.73E-02	7.54E-03	0.26	1.36E-03	0.40	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	3.78E-06
6	0.14	0.60	15.00	6.87E-02	9.04E-03	0.31	1.95E-03	0.37	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	1.34E-06
7	0.16	0.70	15.00	8.02E-02	1.06E-02	0.36	2.66E-03	0.33	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	4.12E-07
8	0.18	0.80	15.00	9.16E-02	1.21E-02	0.41	3.47E-03	0.27	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	9.21E-08
9	0.21	0.90	15.00	1.03E-01	1.36E-02	0.46	4.39E-03	0.20	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	9.58E-09
10	0.23	1.00	15.00	1.15E-01	1.51E-02	0.51	5.42E-03	0.06	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	2.28E-11
											2.5531				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	8.52E-04
0.02	4.04E-04
0.05	9.56E-05
0.07	2.81E-05
0.09	1.01E-05
0.11	3.78E-06
0.14	1.34E-06
0.16	4.12E-07
0.18	9.21E-08
0.21	9.58E-09
0.23	2.28E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 0.307 kilometers

Plume dispersion angle 15 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 2.5 %

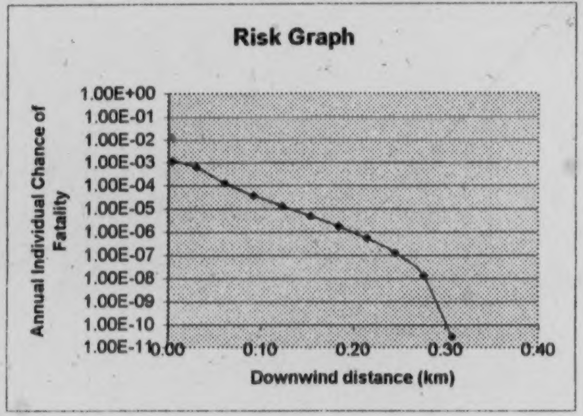
Segment length 5000 m

Volume of gas released 669 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.02	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.61	1.00000	0.98	0.9837	2.6508	7.45E-04	1.00	1.19E-03
1	0.03	0.10	15.00	1.54E-02	2.02E-03	0.07	9.75E-05	0.61	0.94124	0.90	0.8471	1.6671	7.45E-04	1.00	6.43E-04
2	0.06	0.20	15.00	3.07E-02	4.04E-03	0.14	3.90E-04	0.60	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	1.28E-04
3	0.09	0.30	15.00	4.61E-02	6.06E-03	0.21	8.77E-04	0.59	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	3.76E-05
4	0.12	0.40	15.00	6.14E-02	8.08E-03	0.28	1.56E-03	0.56	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	1.35E-05
5	0.15	0.50	15.00	7.68E-02	1.01E-02	0.34	2.44E-03	0.53	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	5.07E-06
6	0.18	0.60	15.00	9.21E-02	1.21E-02	0.41	3.51E-03	0.49	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	1.80E-06
7	0.21	0.70	15.00	1.07E-01	1.41E-02	0.48	4.78E-03	0.44	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	5.52E-07
8	0.25	0.80	15.00	1.23E-01	1.62E-02	0.55	6.24E-03	0.37	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	1.24E-07
9	0.28	0.90	15.00	1.38E-01	1.82E-02	0.62	7.89E-03	0.27	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	1.28E-08
10	0.31	1.00	15.00	1.54E-01	2.02E-02	0.69	9.75E-03	0.09	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	3.06E-11
											2.6508				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	1.19E-03
0.03	6.43E-04
0.06	1.28E-04
0.09	3.76E-05
0.12	1.35E-05
0.15	5.07E-06
0.18	1.80E-06
0.21	5.52E-07
0.25	1.24E-07
0.28	1.28E-08
0.31	3.06E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break)	7.45E-04	failures/km*year
Maximum hazard distance (distance to PD 1%)	0.363	kilometers
Plume dispersion angle	15	degrees
Assumed lethality at source	100	percent
Calibration to existing regulatory policy	1	(1.0 or other factor)

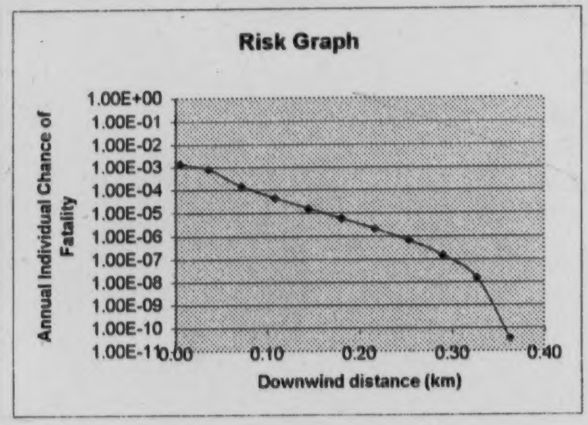
Pipeline data (descriptive only- NOT data inputs)

H2S concentration	2.5	%
Segment length	10000	m
Volume of gas released	1304	(m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.01	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.73	1.00000	0.99	0.9862	2.6980	7.45E-04	1.00	1.44E-03
1	0.04	0.10	15.00	1.82E-02	2.39E-03	0.08	1.36E-04	0.72	0.99090	0.90	0.8918	1.7117	7.45E-04	1.00	8.22E-04
2	0.07	0.20	15.00	3.63E-02	4.78E-03	0.16	5.45E-04	0.71	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	1.52E-04
3	0.11	0.30	15.00	5.45E-02	7.17E-03	0.24	1.23E-03	0.69	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	4.45E-05
4	0.15	0.40	15.00	7.26E-02	9.56E-03	0.33	2.18E-03	0.67	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	1.60E-05
5	0.18	0.50	15.00	9.08E-02	1.19E-02	0.41	3.41E-03	0.63	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	5.99E-06
6	0.22	0.60	15.00	1.09E-01	1.43E-02	0.49	4.90E-03	0.58	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	2.13E-06
7	0.25	0.70	15.00	1.27E-01	1.67E-02	0.57	6.68E-03	0.52	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	6.52E-07
8	0.29	0.80	15.00	1.45E-01	1.91E-02	0.65	8.72E-03	0.44	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	1.46E-07
9	0.33	0.90	15.00	1.63E-01	2.15E-02	0.73	1.10E-02	0.32	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	1.52E-08
10	0.36	1.00	15.00	1.82E-01	2.39E-02	0.81	1.36E-02	0.10	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	3.61E-11
											2.6980				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	1.44E-03
0.04	8.22E-04
0.07	1.52E-04
0.11	4.45E-05
0.15	1.60E-05
0.18	5.99E-06
0.22	2.13E-06
0.25	6.52E-07
0.29	1.46E-07
0.33	1.52E-08
0.36	3.61E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 0.39 kilometers

Plume dispersion angle 15 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 2.5 %

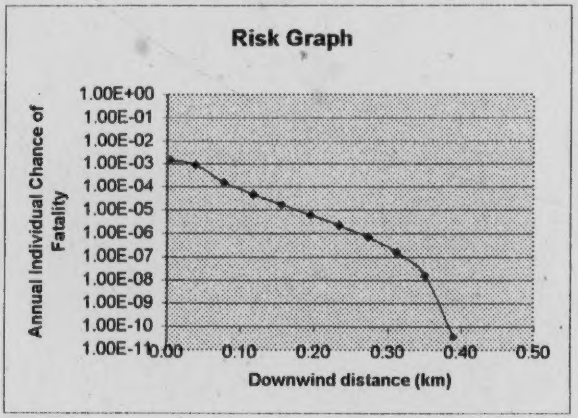
Segment length 20000 m

Volume of gas released 2538 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.01	15.00	2.50E-03	3.29E-04	0.01	2.58E-06	0.78	1.00000	0.99	0.9872	2.7071	7.45E-04	1.00	1.55E-03
1	0.04	0.10	15.00	1.95E-02	2.57E-03	0.09	1.57E-04	0.78	1.00000	0.90	0.9000	1.7199	7.45E-04	1.00	8.95E-04
2	0.08	0.20	15.00	3.90E-02	5.13E-03	0.17	6.29E-04	0.76	0.43583	0.80	0.3487	0.8199	7.45E-04	1.00	1.63E-04
3	0.12	0.30	15.00	5.85E-02	7.70E-03	0.26	1.42E-03	0.74	0.26150	0.70	0.1830	0.4713	7.45E-04	1.00	4.78E-05
4	0.16	0.40	15.00	7.80E-02	1.03E-02	0.35	2.52E-03	0.71	0.18678	0.60	0.1121	0.2882	7.45E-04	1.00	1.72E-05
5	0.20	0.50	15.00	9.75E-02	1.28E-02	0.44	3.93E-03	0.68	0.14528	0.50	0.0726	0.1762	7.45E-04	1.00	6.44E-06
6	0.23	0.60	15.00	1.17E-01	1.54E-02	0.52	5.66E-03	0.62	0.11886	0.40	0.0475	0.1035	7.45E-04	1.00	2.29E-06
7	0.27	0.70	15.00	1.37E-01	1.80E-02	0.61	7.71E-03	0.56	0.10058	0.30	0.0302	0.0560	7.45E-04	1.00	7.01E-07
8	0.31	0.80	15.00	1.56E-01	2.05E-02	0.70	1.01E-02	0.47	0.08717	0.20	0.0174	0.0258	7.45E-04	1.00	1.57E-07
9	0.35	0.90	15.00	1.76E-01	2.31E-02	0.79	1.27E-02	0.34	0.07691	0.10	0.0077	0.0084	7.45E-04	1.00	1.63E-08
10	0.39	1.00	15.00	1.95E-01	2.57E-02	0.87	1.57E-02	0.11	0.06881	0.01	0.0007	0.0007	7.45E-04	1.00	3.88E-11
											2.7071				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	1.55E-03
0.04	8.95E-04
0.08	1.63E-04
0.12	4.78E-05
0.16	1.72E-05
0.20	6.44E-06
0.23	2.29E-06
0.27	7.01E-07
0.31	1.57E-07
0.35	1.63E-08
0.39	3.88E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 0.641 kilometers

Plume dispersion angle 30 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 30 %

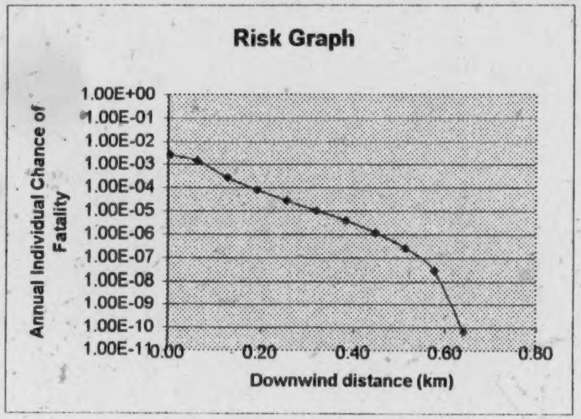
Segment length 500 m

Volume of gas released 2538 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.01	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	1.28	1.00000	0.99	0.9922	2.7266	7.45E-04	1.00	2.58E-03
1	0.06	0.10	30.00	3.21E-02	8.59E-03	0.15	8.65E-04	1.28	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	1.48E-03
2	0.13	0.20	30.00	6.41E-02	1.72E-02	0.29	3.46E-03	1.26	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	2.77E-04
3	0.19	0.30	30.00	9.62E-02	2.58E-02	0.44	7.78E-03	1.22	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	8.14E-05
4	0.26	0.40	30.00	1.28E-01	3.44E-02	0.59	1.38E-02	1.17	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	2.93E-05
5	0.32	0.50	30.00	1.60E-01	4.29E-02	0.74	2.16E-02	1.11	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	1.10E-05
6	0.38	0.60	30.00	1.92E-01	5.15E-02	0.88	3.11E-02	1.03	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	3.89E-06
7	0.45	0.70	30.00	2.24E-01	6.01E-02	1.03	4.24E-02	0.92	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	1.19E-06
8	0.51	0.80	30.00	2.56E-01	6.87E-02	1.18	5.53E-02	0.77	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	2.67E-07
9	0.58	0.90	30.00	2.88E-01	7.73E-02	1.33	7.00E-02	0.56	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	2.78E-08
10	0.64	1.00	30.00	3.21E-01	8.59E-02	1.47	8.65E-02	0.18	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	6.61E-11
											2.7266				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	2.58E-03
0.06	1.48E-03
0.13	2.77E-04
0.19	8.14E-05
0.26	2.93E-05
0.32	1.10E-05
0.38	3.89E-06
0.45	1.19E-06
0.51	2.67E-07
0.58	2.78E-08
0.64	6.61E-11


Risk Graph

Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 0.935 kilometers

Plume dispersion angle 30 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 30 %

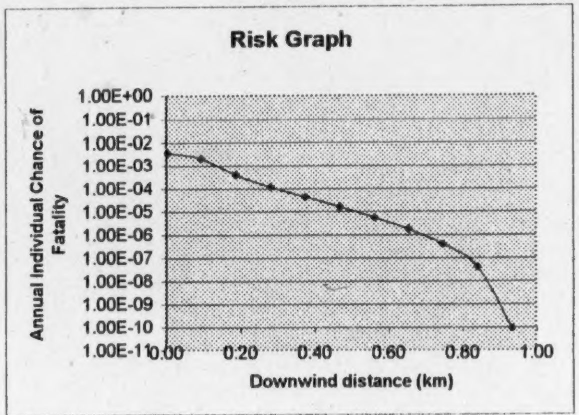
Segment length 1000 m

Volume of gas released 3554 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.01	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	1.87	1.00000	0.99	0.9947	2.7291	7.45E-04	1.00	3.78E-03
1	0.09	0.10	30.00	4.68E-02	1.25E-02	0.22	1.84E-03	1.86	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	2.16E-03
2	0.19	0.20	30.00	9.35E-02	2.51E-02	0.43	7.36E-03	1.83	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	4.04E-04
3	0.28	0.30	30.00	1.40E-01	3.76E-02	0.65	1.66E-02	1.78	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	1.19E-04
4	0.37	0.40	30.00	1.87E-01	5.01E-02	0.86	2.94E-02	1.71	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	4.27E-05
5	0.47	0.50	30.00	2.34E-01	6.26E-02	1.08	4.60E-02	1.62	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	1.60E-05
6	0.56	0.60	30.00	2.81E-01	7.52E-02	1.29	6.62E-02	1.50	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	5.68E-06
7	0.65	0.70	30.00	3.27E-01	8.77E-02	1.51	9.01E-02	1.34	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	1.74E-06
8	0.75	0.80	30.00	3.74E-01	1.00E-01	1.72	1.18E-01	1.12	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	3.90E-07
9	0.84	0.90	30.00	4.21E-01	1.13E-01	1.94	1.49E-01	0.82	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	4.05E-08
10	0.94	1.00	30.00	4.68E-01	1.25E-01	2.15	1.84E-01	0.26	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	9.64E-11
											2.7291				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	3.78E-03
0.09	2.16E-03
0.19	4.04E-04
0.28	1.19E-04
0.37	4.27E-05
0.47	1.60E-05
0.56	5.68E-06
0.65	1.74E-06
0.75	3.90E-07
0.84	4.05E-08
0.94	9.64E-11



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break)	7.45E-04	failures/km*year
Maximum hazard distance (distance to PD 1%)	1.599	kilometers
Plume dispersion angle	30	degrees
Assumed lethality at source	100	percent
Calibration to existing regulatory policy	1	(1.0 or other factor)

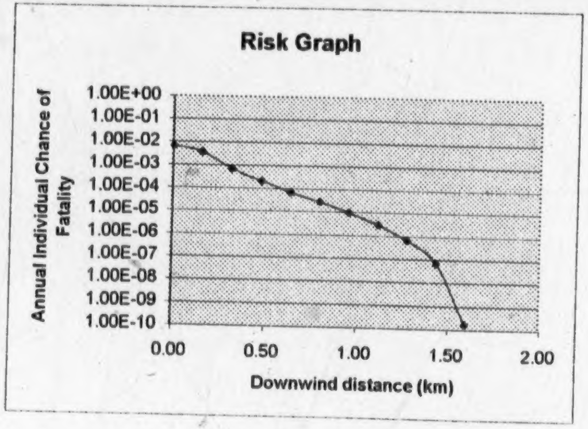
Pipeline data (descriptive only- NOT data inputs)

H2S concentration	30	%
Segment length	2500	m
Volume of gas released	7135	(m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.00	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	3.20	1.00000	1.00	0.9969	2.7313	7.45E-04	1.00	6.49E-03
1	0.16	0.10	30.00	8.00E-02	2.14E-02	0.37	5.38E-03	3.18	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	3.70E-03
2	0.32	0.20	30.00	1.60E-01	4.28E-02	0.74	2.15E-02	3.13	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	6.91E-04
3	0.48	0.30	30.00	2.40E-01	6.43E-02	1.10	4.84E-02	3.05	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	2.03E-04
4	0.64	0.40	30.00	3.20E-01	8.57E-02	1.47	8.61E-02	2.93	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	7.30E-05
5	0.80	0.50	30.00	4.00E-01	1.07E-01	1.84	1.35E-01	2.77	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	2.73E-05
6	0.96	0.60	30.00	4.80E-01	1.29E-01	2.21	1.94E-01	2.56	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	9.72E-06
7	1.12	0.70	30.00	5.60E-01	1.50E-01	2.57	2.64E-01	2.28	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	2.98E-06
8	1.28	0.80	30.00	6.40E-01	1.71E-01	2.94	3.44E-01	1.92	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	6.66E-07
9	1.44	0.90	30.00	7.20E-01	1.93E-01	3.31	4.36E-01	1.39	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	6.93E-08
10	1.60	1.00	30.00	8.00E-01	2.14E-01	3.68	5.38E-01	0.45	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	1.65E-10
											2.7313				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	6.49E-03
0.16	3.70E-03
0.32	6.91E-04
0.48	2.03E-04
0.64	7.30E-05
0.80	2.73E-05
0.96	9.72E-06
1.12	2.98E-06
1.28	6.66E-07
1.44	6.93E-08
1.60	1.65E-10



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 2.209 kilometers

Plume dispersion angle 30 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 30 %

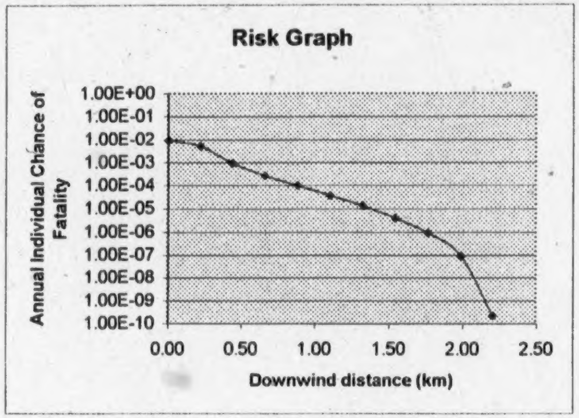
Segment length 5000 m

Volume of gas released 13534 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.00	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	4.42	1.00000	1.00	0.9977	2.7321	7.45E-04	1.00	8.97E-03
1	0.22	0.10	30.00	1.10E-01	2.96E-02	0.51	1.03E-02	4.40	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	5.11E-03
2	0.44	0.20	30.00	2.21E-01	5.92E-02	1.02	4.11E-02	4.33	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	9.55E-04
3	0.66	0.30	30.00	3.31E-01	8.88E-02	1.52	9.24E-02	4.21	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	2.81E-04
4	0.88	0.40	30.00	4.42E-01	1.18E-01	2.03	1.64E-01	4.05	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	1.01E-04
5	1.10	0.50	30.00	5.52E-01	1.48E-01	2.54	2.57E-01	3.83	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	3.78E-05
6	1.33	0.60	30.00	6.63E-01	1.78E-01	3.05	3.70E-01	3.53	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	1.34E-05
7	1.55	0.70	30.00	7.73E-01	2.07E-01	3.56	5.03E-01	3.16	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	4.11E-06
8	1.77	0.80	30.00	8.84E-01	2.37E-01	4.06	6.57E-01	2.65	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	9.20E-07
9	1.99	0.90	30.00	9.94E-01	2.66E-01	4.57	8.32E-01	1.93	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	9.57E-08
10	2.21	1.00	30.00	1.10E+00	2.96E-01	5.08	1.03E+00	0.62	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	2.28E-10
											2.7321				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	8.97E-03
0.22	5.11E-03
0.44	9.55E-04
0.66	2.81E-04
0.88	1.01E-04
1.10	3.78E-05
1.33	1.34E-05
1.55	4.11E-06
1.77	9.20E-07
1.99	9.57E-08
2.21	2.28E-10



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break)	7.45E-04	failures/km*year
Maximum hazard distance (distance to PD 1%)	2.612	kilometers
Plume dispersion angle	30	degrees
Assumed lethality at source	100	percent
Calibration to existing regulatory policy	1	(1.0 or other factor)

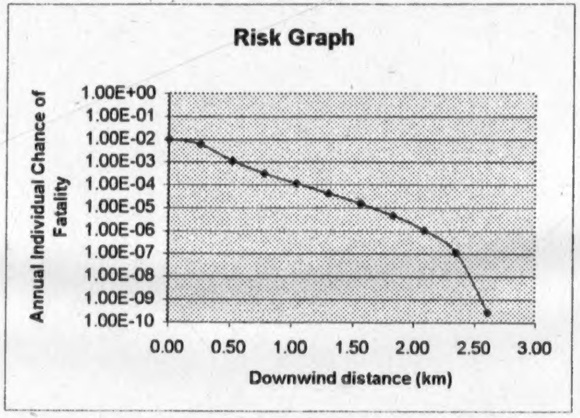
Pipeline data (descriptive only- NOT data inputs)

H2S concentration	30	%
Segment length	10000	m
Volume of gas released	26879	(m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.00	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	5.22	1.00000	1.00	0.9981	2.7325	7.45E-04	1.00	1.06E-02
1	0.26	0.10	30.00	1.31E-01	3.50E-02	0.60	1.44E-02	5.20	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	6.04E-03
2	0.52	0.20	30.00	2.61E-01	7.00E-02	1.20	5.74E-02	5.12	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	1.13E-03
3	0.78	0.30	30.00	3.92E-01	1.05E-01	1.80	1.29E-01	4.98	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	3.32E-04
4	1.04	0.40	30.00	5.22E-01	1.40E-01	2.40	2.30E-01	4.79	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	1.19E-04
5	1.31	0.50	30.00	6.53E-01	1.75E-01	3.00	3.59E-01	4.52	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	4.47E-05
6	1.57	0.60	30.00	7.84E-01	2.10E-01	3.60	5.17E-01	4.18	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	1.59E-05
7	1.83	0.70	30.00	9.14E-01	2.45E-01	4.20	7.04E-01	3.73	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	4.86E-06
8	2.09	0.80	30.00	1.04E+00	2.80E-01	4.81	9.19E-01	3.13	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	1.09E-06
9	2.35	0.90	30.00	1.18E+00	3.15E-01	5.41	1.16E+00	2.28	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	1.13E-07
10	2.61	1.00	30.00	1.31E+00	3.50E-01	6.01	1.44E+00	0.74	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	2.69E-10
											2.7325				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	1.06E-02
0.26	6.04E-03
0.52	1.13E-03
0.78	3.32E-04
1.04	1.19E-04
1.31	4.47E-05
1.57	1.59E-05
1.83	4.86E-06
2.09	1.09E-06
2.35	1.13E-07
2.61	2.69E-10



Risk in an oval plume

Input Data

Frequency of hazard (pipeline break) 7.45E-04 failures/km*year

Maximum hazard distance (distance to PD 1%) 2.879 kilometers

Plume dispersion angle 30 degrees

Assumed lethality at source 100 percent

Calibration to existing regulatory policy 1 (1.0 or other factor)

Pipeline data (descriptive only- NOT data inputs)

H2S concentration 30 %

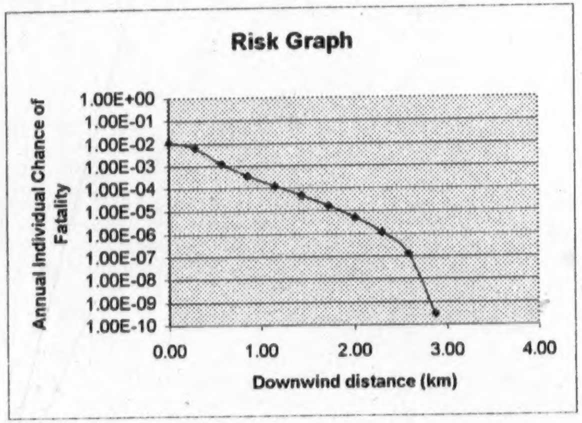
Segment length 20000 m

Volume of gas released 53598 (m^3)

Step	Downwind distance (km)	Prorated hazard distance	plume angle	(length -x) major axis	(height -y) minor axis	circumference (km)	area (km^2)	pipeline interaction length(km)	probability of exposure	probability of fatality per failure	Pe*Pd	sum of plumes	failure frequency	probability of non-ignition	annual individual chance of fatality
0	0.005	0.00	30.00	2.50E-03	6.70E-04	0.01	5.26E-06	5.76	1.00000	1.00	0.9983	2.7327	7.45E-04	1.00	1.17E-02
1	0.29	0.10	30.00	1.44E-01	3.86E-02	0.66	1.74E-02	5.73	1.00000	0.90	0.9000	1.7344	7.45E-04	1.00	6.66E-03
2	0.58	0.20	30.00	2.88E-01	7.71E-02	1.32	6.98E-02	5.64	0.44351	0.80	0.3548	0.8344	7.45E-04	1.00	1.24E-03
3	0.86	0.30	30.00	4.32E-01	1.16E-01	1.99	1.57E-01	5.49	0.26611	0.70	0.1863	0.4796	7.45E-04	1.00	3.66E-04
4	1.15	0.40	30.00	5.76E-01	1.54E-01	2.65	2.79E-01	5.28	0.19008	0.60	0.1140	0.2933	7.45E-04	1.00	1.32E-04
5	1.44	0.50	30.00	7.20E-01	1.93E-01	3.31	4.36E-01	4.99	0.14784	0.50	0.0739	0.1793	7.45E-04	1.00	4.92E-05
6	1.73	0.60	30.00	8.64E-01	2.31E-01	3.97	6.28E-01	4.61	0.12096	0.40	0.0484	0.1054	7.45E-04	1.00	1.75E-05
7	2.02	0.70	30.00	1.01E+00	2.70E-01	4.63	8.55E-01	4.11	0.10235	0.30	0.0307	0.0570	7.45E-04	1.00	5.36E-06
8	2.30	0.80	30.00	1.15E+00	3.09E-01	5.30	1.12E+00	3.45	0.08870	0.20	0.0177	0.0263	7.45E-04	1.00	1.20E-06
9	2.59	0.90	30.00	1.30E+00	3.47E-01	5.96	1.41E+00	2.51	0.07827	0.10	0.0078	0.0085	7.45E-04	1.00	1.25E-07
10	2.88	1.00	30.00	1.44E+00	3.86E-01	6.62	1.74E+00	0.81	0.07003	0.01	0.0007	0.0007	7.45E-04	1.00	2.97E-10
											2.7327				

Data for Risk Graph

Downwind distance (km)	annual individual risk of fatality
0.01	1.17E-02
0.29	6.66E-03
0.58	1.24E-03
0.86	3.66E-04
1.15	1.32E-04
1.44	4.92E-05
1.73	1.75E-05
2.02	5.36E-06
2.30	1.20E-06
2.59	1.25E-07
2.88	2.97E-10



Appendix 3 – Risk Calculations

TABLE 1 - Twice the distance to a probability of lethality of 1% used as the interaction length. Data in CHARTS 1, 2, 3, 4

Case	Frequency of p/l rupture failures/km/yr	Interaction length (km)	Probability non-ignition	Probability emission rate	Probability release geometry	Probability meteorology	Probability wind direction	Probability outside receptor	Probability fatality	Individual risk	Annual chance of fatality (1 in
2.5% H2S p/l rupture on ROW	7.45E-04	0.2140	1.0	1.0	1.0	0.209	0.28	1.0	1.00	9.33E-06	107183
2.5% H2S p/l rupture at 107m	7.45E-04	0.2140	1.0	1.0	1.0	0.209	0.28	1.0	0.01	9.33E-08	10718293
2.5% H2S p/l rupture on ROW	7.45E-04	0.3180	1.0	1.0	1.0	0.209	0.28	1.0	1.00	1.39E-05	72129
2.5% H2S p/l rupture at 159m	7.45E-04	0.3180	1.0	1.0	1.0	0.209	0.28	1.0	0.01	1.39E-07	7212940
2.5% H2S p/l rupture on ROW	7.45E-04	0.4580	1.0	1.0	1.0	0.209	0.28	1.0	1.00	2.00E-05	50081
2.5% H2S p/l rupture at 229m	7.45E-04	0.4580	1.0	1.0	1.0	0.209	0.28	1.0	0.01	2.00E-07	5008111
2.5% H2S p/l rupture on ROW	7.45E-04	0.6140	1.0	1.0	1.0	0.209	0.28	1.0	1.00	2.68E-05	37357
2.5% H2S p/l rupture at 307m	7.45E-04	0.6140	1.0	1.0	1.0	0.209	0.28	1.0	0.01	2.68E-07	3735692
2.5% H2S p/l rupture on ROW	7.45E-04	0.7260	1.0	1.0	1.0	0.209	0.28	1.0	1.00	3.17E-05	31594
2.5% H2S p/l rupture at 363m	7.45E-04	0.7260	1.0	1.0	1.0	0.209	0.28	1.0	0.01	3.17E-07	3159387
2.5% H2S p/l rupture on ROW	7.45E-04	0.7800	1.0	1.0	1.0	0.209	0.28	1.0	1.00	3.40E-05	29407
2.5% H2S p/l rupture at 390m	7.45E-04	0.7800	1.0	1.0	1.0	0.209	0.28	1.0	0.01	3.40E-07	2940660
30% H2S p/l rupture on ROW	7.45E-04	1.2800	1.0	1.0	1.0	0.209	0.28	1.0	1.00	5.58E-05	17920
30% H2S p/l rupture at 641m	7.45E-04	1.2800	1.0	1.0	1.0	0.209	0.28	1.0	0.01	5.58E-07	1791965
30% H2S p/l rupture on ROW	7.45E-04	1.8700	1.0	1.0	1.0	0.209	0.28	1.0	1.00	8.15E-05	12266
30% H2S p/l rupture at 935m	7.45E-04	1.8700	1.0	1.0	1.0	0.209	0.28	1.0	0.01	8.15E-07	1226585
30% H2S p/l rupture on ROW	7.45E-04	3.1980	1.0	1.0	1.0	0.209	0.28	1.0	1.00	1.39E-04	7172
30% H2S p/l rupture at 1599m	7.45E-04	3.1980	1.0	1.0	1.0	0.209	0.28	1.0	0.01	1.39E-06	717234
30% H2S p/l rupture on ROW	7.45E-04	4.4180	1.0	1.0	1.0	0.209	0.28	1.0	1.00	1.93E-04	5192
30% H2S p/l rupture at 2209m	7.45E-04	4.4180	1.0	1.0	1.0	0.209	0.28	1.0	0.01	1.93E-06	519175
30% H2S p/l rupture on ROW	7.45E-04	5.2240	1.0	1.0	1.0	0.209	0.28	1.0	1.00	2.28E-04	4391
30% H2S p/l rupture at 2612m	7.45E-04	5.2240	1.0	1.0	1.0	0.209	0.28	1.0	0.01	2.28E-06	439073
30% H2S p/l rupture on ROW	7.45E-04	5.7580	1.0	1.0	1.0	0.209	0.28	1.0	1.00	2.51E-04	3984
30% H2S p/l rupture at 2879m	7.45E-04	5.7580	1.0	1.0	1.0	0.209	0.28	1.0	0.01	2.51E-06	398353

Distance from p/l to 1%lethality	Annual risk
107	9.33E-08
159	1.39E-07
229	2.00E-07
307	2.68E-07
363	3.17E-07
390	3.40E-07
641	5.58E-07
935	8.15E-07
1599	1.39E-06
2209	1.93E-06
2612	2.28E-06
2879	2.51E-06

Chart 1(total) chart 2 (2.5%)

Release Volume (m^3)	Annual risk
142	9.33E-08
191	1.39E-07
364	2.00E-07
669	2.68E-07
1304	3.17E-07
2586	3.40E-07
2538	5.58E-07
3554	8.15E-07
7135	1.39E-06
13534	1.93E-06
26879	2.28E-06
53598	2.51E-06

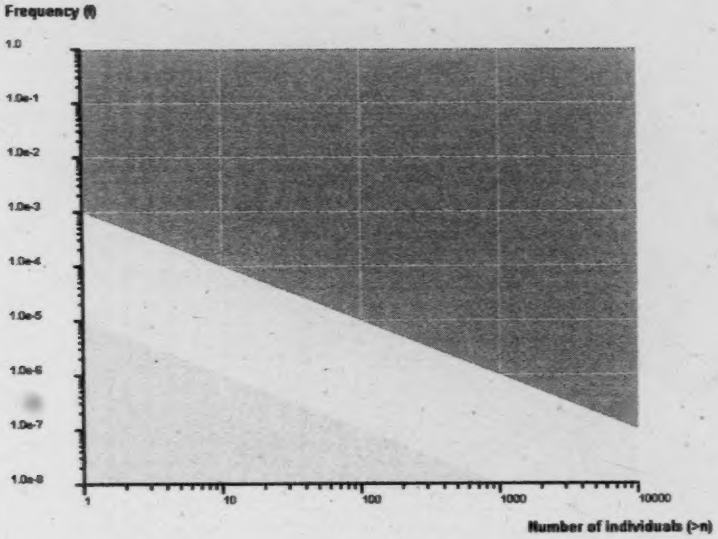
Standing on ROW 100%lethality (Chart 3 (total) and Chart 4(2.5%))

Release Volume (m^3)	Annual Risk
142	9.33E-06
191	1.39E-05
364	2.00E-05
669	2.68E-05
1304	3.17E-05
2586	3.40E-05
2538	5.58E-05
3554	8.15E-05
7135	1.39E-04
13534	1.93E-04
26879	2.28E-04
53598	2.51E-04

Appendix 4 – Societal Risk Data (FN Curves) generated with Shell Global Solutions PRTlite Software

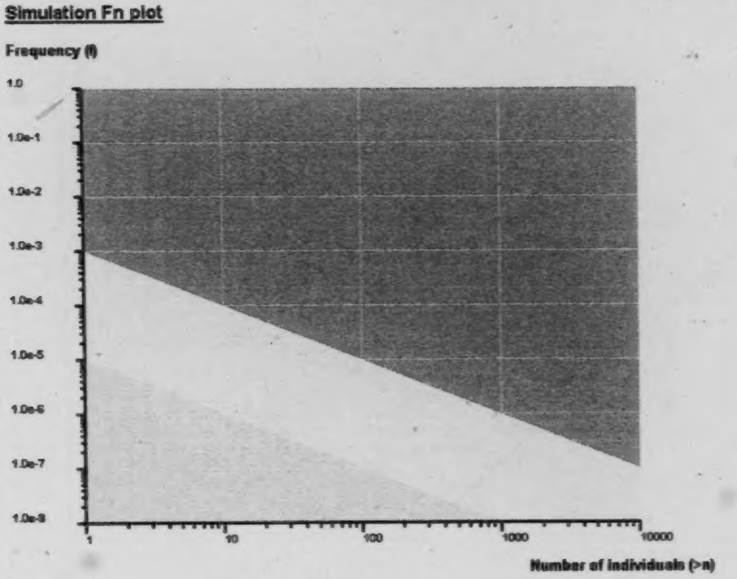
2.5% H_2S
Undeveloped Rural (100m setback)
Density 1e-6/m2

Simulation Fn plot



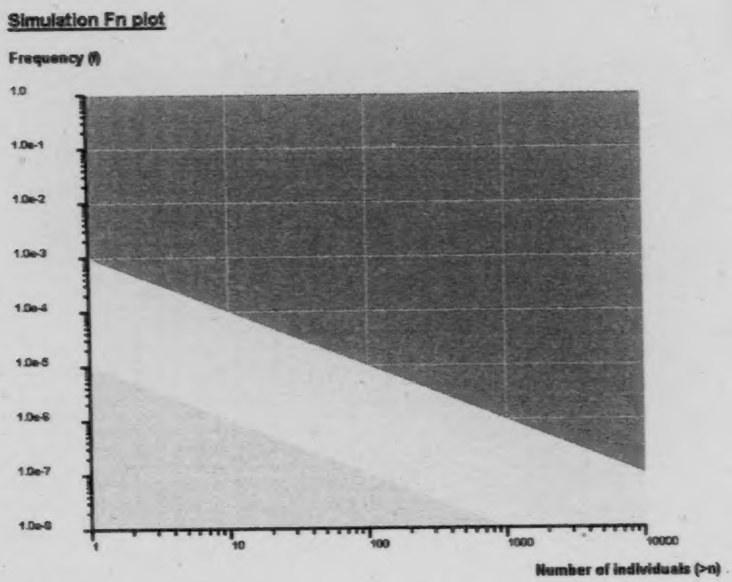
500m
1000m
2500m
5000m
10000m
20000m

30% H_2S
Undeveloped Rural (100m setback)
Density 1e-6/m2



500m
1000m
2500m
5000m
10000m
20000m

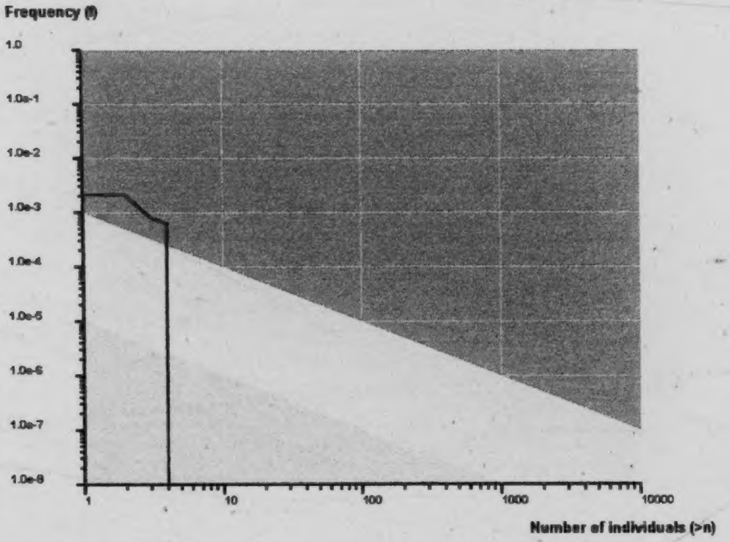
2.5% H_2S
Developed Rural (100m setback)
Density 5e-5/m2



500m valve spacing
1000m
2500m
5000m
10000m
20000m

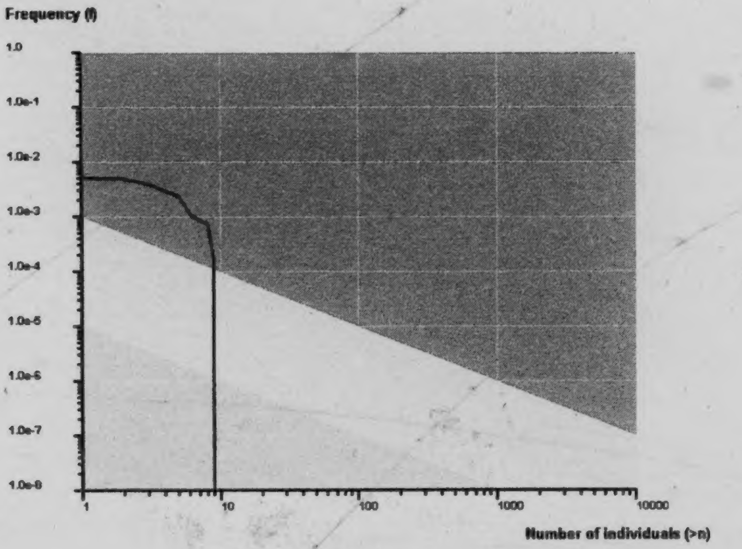
30% H_2S
Developed Rural (100m setback)
Density 5e-5/m2

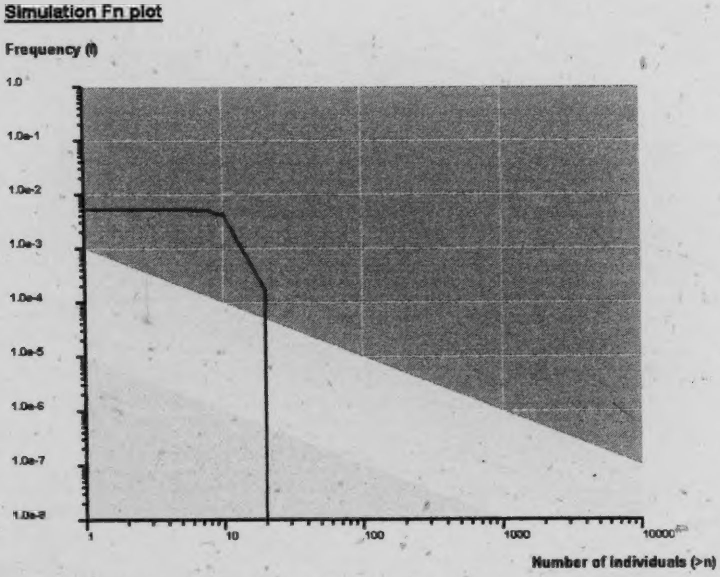
Simulation Fn plot



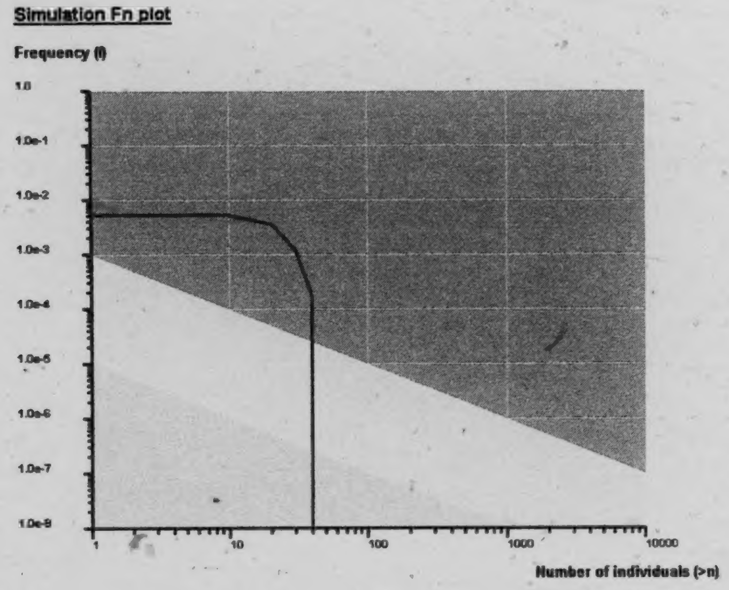
500m above / 1000m below

Simulation Fn plot

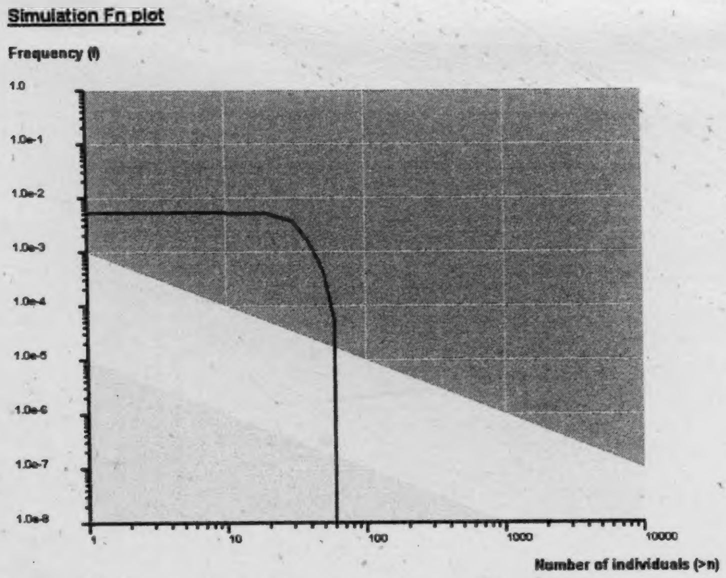



Simulation Fn plot
Frequency (f)
1.0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
1.0e-6
1.0e-7
1.0e-8
1
10
100
1000
10000
Number of individuals (>n)

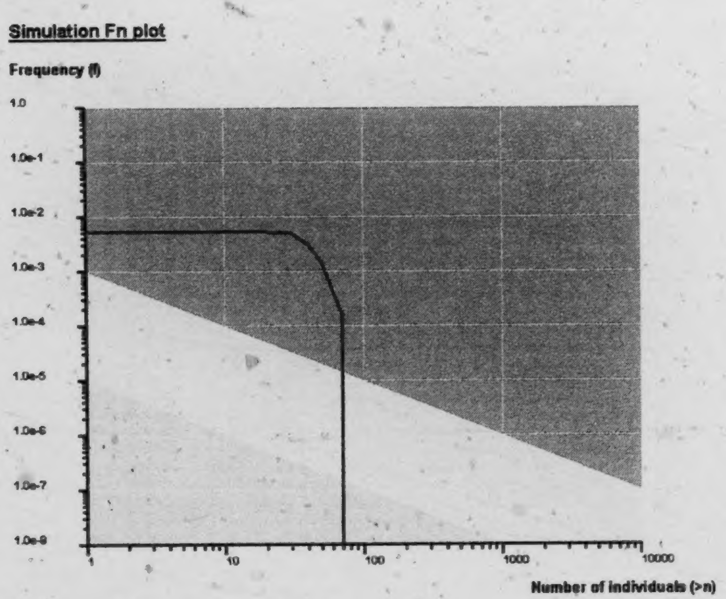
2500m


Simulation Fn plot
Frequency (f)
1.0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
1.0e-6
1.0e-7
1.0e-8
1
10
100
1000
10000
Number of individuals (>n)

5000m

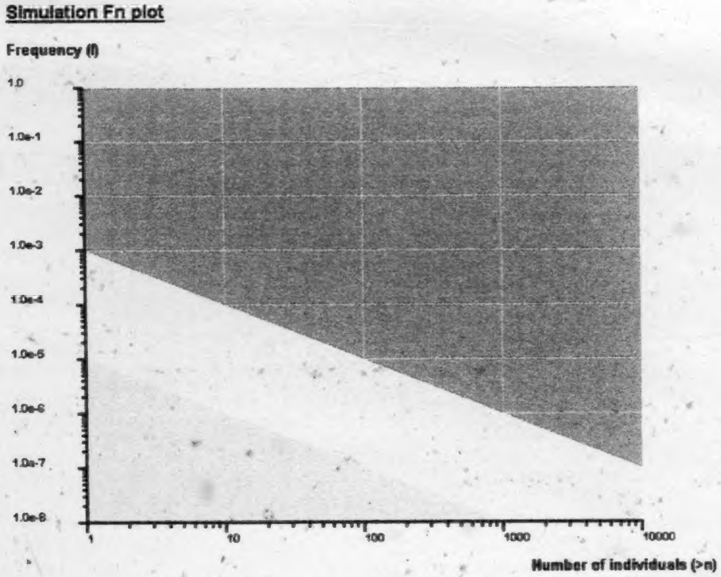


10000m



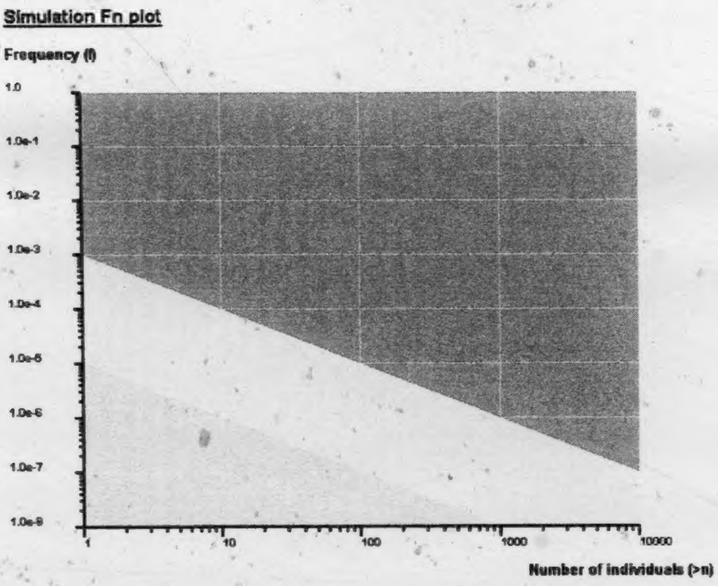
20000m

2.5% H_2S
Urban (1500m setback)
Density 1e-3/m2

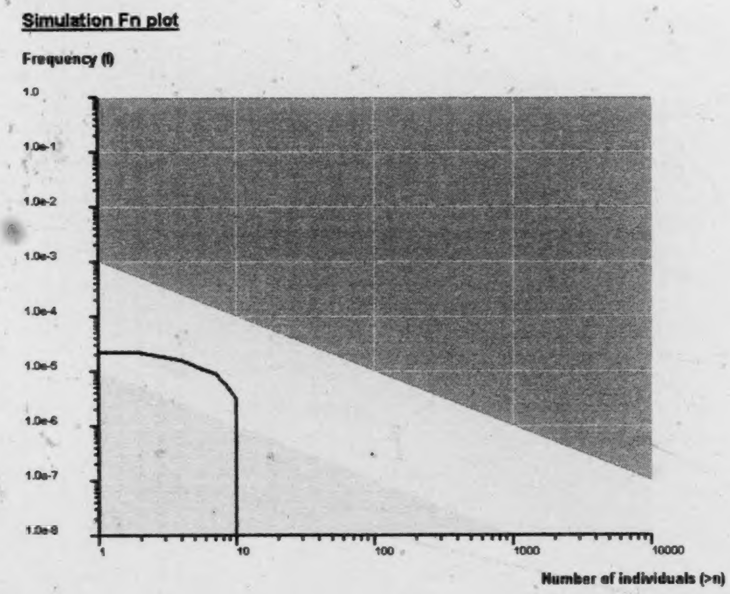


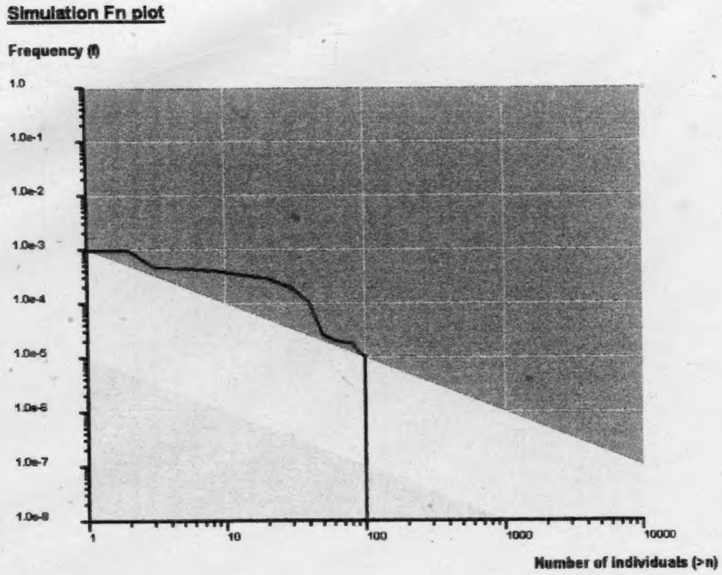
500m valve spacing
1000m
2500m
5000m
10000m
20000m

30% H_2S
Urban (1500m setback)
Density 1e-3/m2

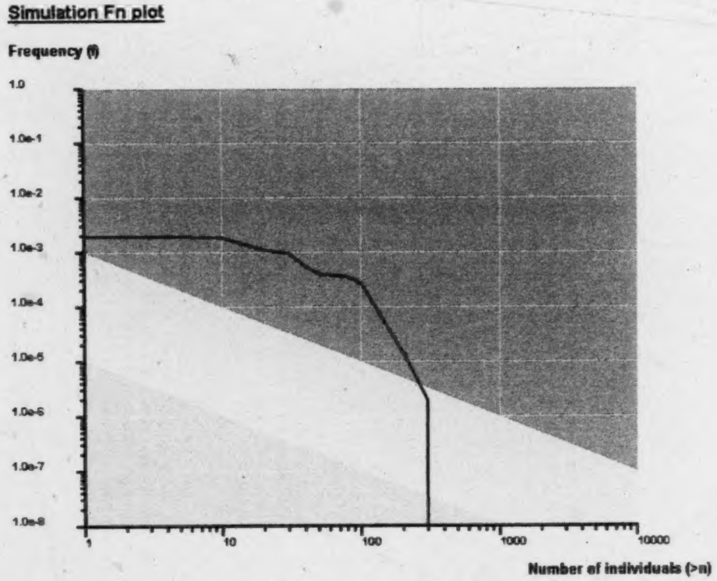


500m and 1000m above
2500m below



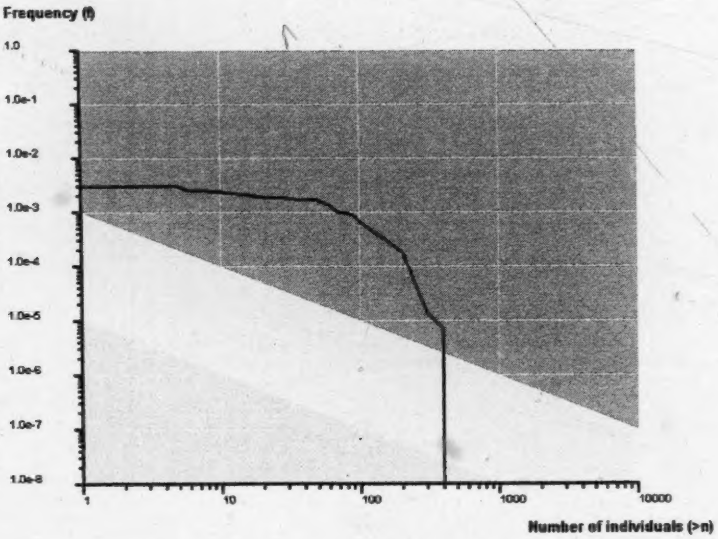


5000m



10000m

Simulation Fn plot



20000m

Data for presentation of FN curves in semilog format as opposed to log/log format

30% H2S - Developed Rural (Density 5e-5/m2) setback 100m

Number of individuals	Frequency	Valve spacing 10000m
1	5.50E-03	
9	5.50E-03	
10	5.50E-03	
20	5.00E-03	
30	3.00E-03	
40	1.00E-03	
50	4.00E-04	
60	6.00E-05	
60	1.00E-08	
1	1.00E-05	
1000	1.00E-08	
1	1.00E-03	
1.00E+05	1.00E-08	

30% H2S - Developed Rural (Density 5e-5/m2) setback 100m

Number of individuals	Frequency	Valve spacing 20000m
1	5.50E-03	
20	5.50E-03	
30	5.00E-03	
40	2.00E-03	
50	1.00E-03	
60	6.00E-04	
70	2.00E-04	
70	1.00E-08	

30% H2S -Urban (1500m setback) (Density 1e-3/m2)

Number of individuals	Frequency	Valve spacing 10000m
1	1.90E-03	
5	1.90E-03	
6	1.70E-03	
10	1.70E-03	
20	1.10E-03	
30	1.00E-03	
40	6.00E-04	
50	4.00E-04	
60	3.00E-04	
70	2.60E-04	
80	2.00E-04	
90	1.80E-04	
100	1.50E-04	
200	1.80E-05	
300	2.00E-06	
300	1.00E-08	

30% H2S -Urban (1500m setback) (Density 1e-3/m2)

Number of individuals	Frequency	Valve spacing 20000m
1	3.00E-03	
5	3.00E-03	
6	2.80E-03	
7	2.80E-03	
8	2.50E-03	
10	2.50E-03	
20	2.00E-03	
30	2.00E-03	
40	1.60E-03	
50	1.60E-03	
60	1.30E-03	
70	1.00E-03	
80	1.00E-03	
90	8.00E-04	
100	6.00E-04	
200	2.00E-04	
300	4.00E-05	
400	7.00E-06	
400	1.00E-08	

Appendix 5 – Derivation of the Time/Concentration Curves

Triple Shifted Rijmond Y = -36.20 +2.366Ln(C^2.5 t)

Concentration (ppm)	Time(min)	Load = C^2.5 t	Probit (Y)	
100	3	300000	0	-6.3611
100	30	3000000	0	-0.91319
500	6.5	36336104.63	4.988091	
300	30	46765371.8	5.585106	
300	3	4676537.18	0.13719	
600	30	264544892.2	9.685072	

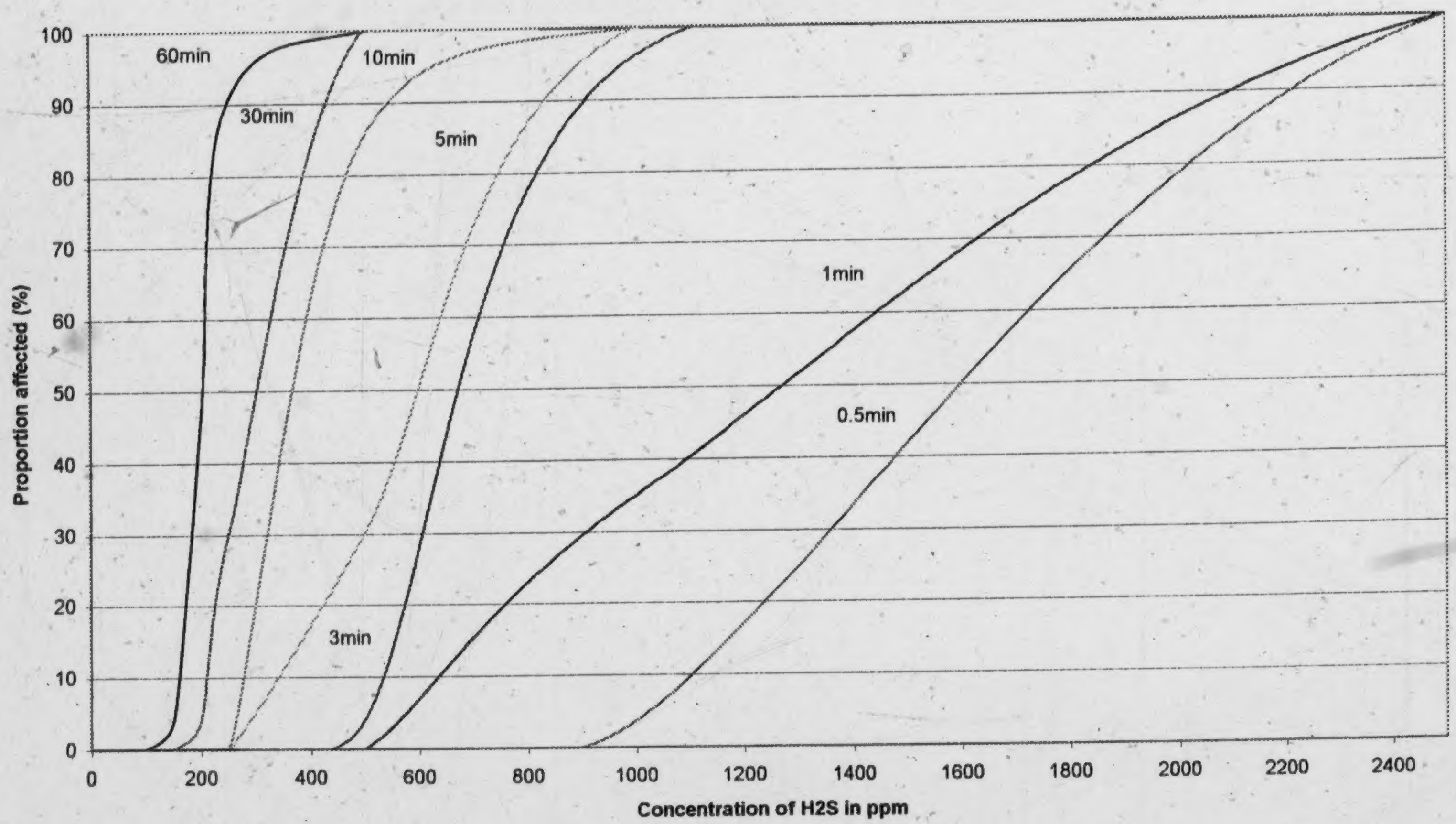
Determination of Probit Value based on Triple Shifted Rijnmond Equation

	Time Exposed to H2S in minutes						
Concentration(ppm	**60**	**30**	**10**	**5**	**3**	**1**	**0.5**
2	-22.41	-24.05	-26.65	-28.29	-29.50	-32.10	-33.74
5	-16.99	-18.63	-21.23	-22.87	-24.08	-26.68	-28.32
10	-12.89	-14.53	-17.13	-18.77	-19.98	-22.58	-24.22
50	-3.37	-5.01	-7.61	-9.25	-10.46	-13.06	-14.70
100	0.73	-0.91	-3.51	-5.15	-6.36	-8.96	-10.60
150	3.13	1.49	-1.11	-2.75	-3.96	-6.56	-8.20
200	4.83	3.19	0.59	-1.05	-2.26	-4.86	-6.50
250	6.15	4.51	1.91	0.27	-0.94	-3.54	-5.18
500	10.25	8.61	6.01	4.37	3.16	0.56	-1.08
1000	14.35	12.71	10.11	8.47	7.26	4.66	3.02
2500	19.77	18.13	15.53	13.89	12.68	10.08	8.44
5000	23.87	22.23	19.63	17.99	16.78	14.18	12.54
7500	26.26	24.62	22.03	20.39	19.18	16.58	14.94
10000	27.97	26.33	23.73	22.09	20.88	18.28	16.64

Determination of Proportion of the Population Affected after COVO

	Time Exposed to H2S in minutes						
Concentration(ppm	**60**	**30**	**10**	**5**	**3**	**1**	**0.5**
2	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0
100	0.05	0	0	0	0	0	0
150	4	0.08	0	0	0	0	0
200	45	4	0	0	0	0	0
250	90	30	0.1	0	0	0	0
500	100	100	85	30	4	0	0
1000	100	100	100	100	96	35	3.7
2500	100	100	100	100	100	100	100
5000	100	100	100	100	100	100	100
7500	100	100	100	100	100	100	100
10000	100	100	100	100	100	100	100

Figure 6.11 - Lethality Curves (based on the TSR) for varying exposure times



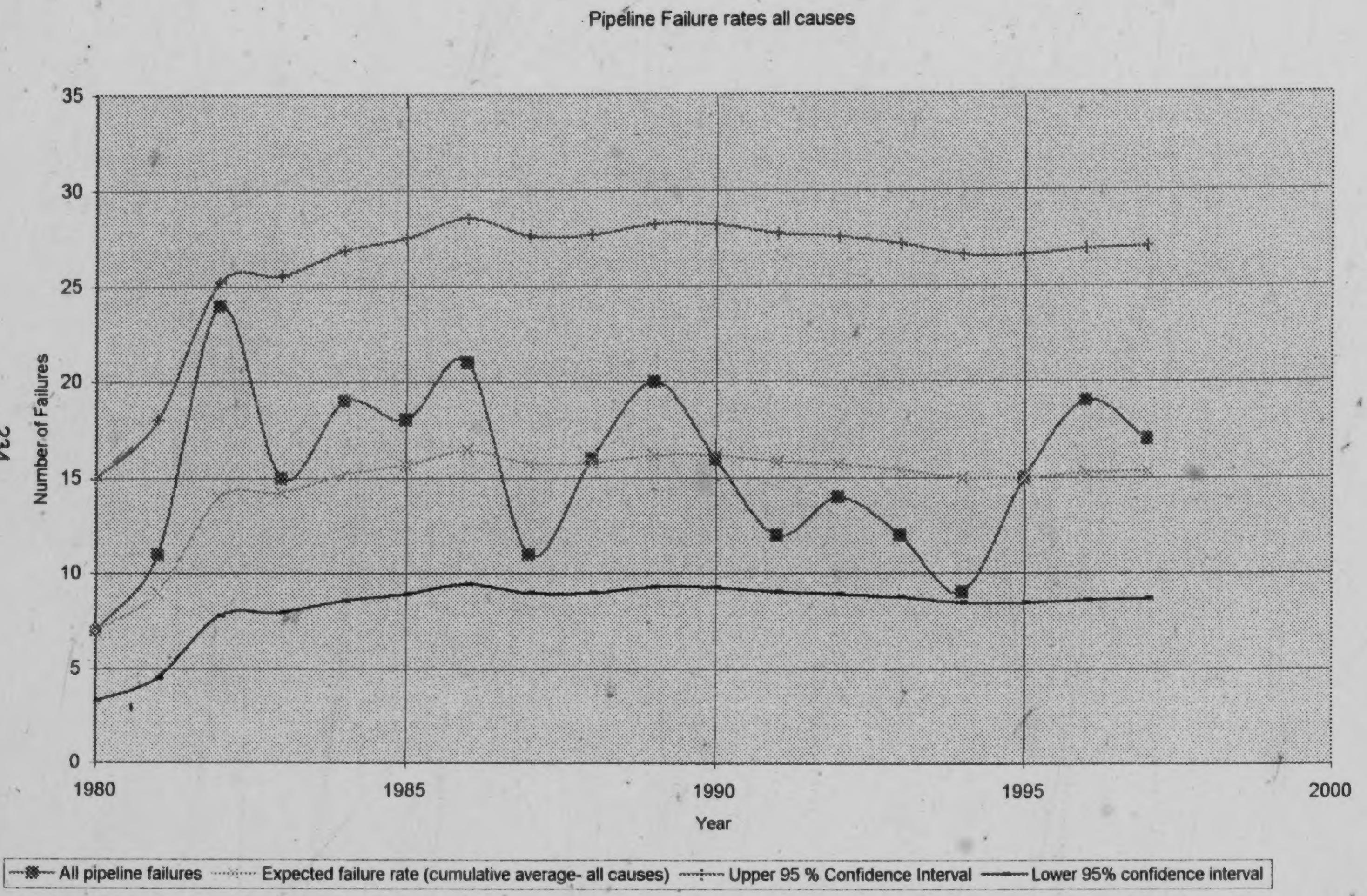
Appendix 6 – Poisson Analysis of Pipeline Failure Data

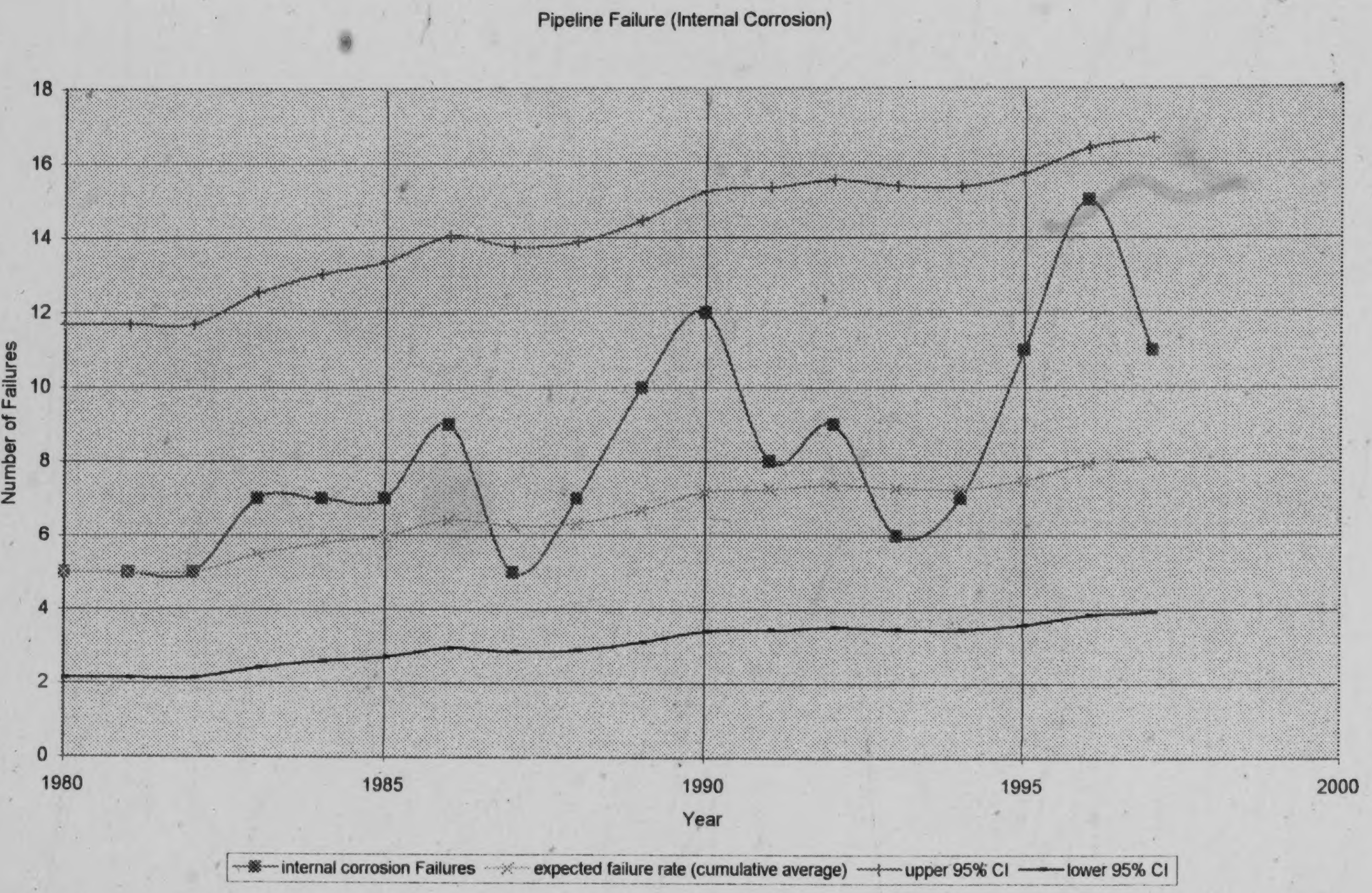
Year	All Failures	Cumulative Average (FE)	UC 95%	LC 95%
1980	7	7.00	14.94	3.28
1981	11	9.00	18.00	4.50
1982	24	14.00	25.22	7.77
1983	15	14.25	25.57	7.94
1984	19	15.20	26.90	8.59
1985	18	15.67	27.54	8.91
1986	21	16.43	28.59	9.44
1987	11	15.75	27.66	8.97
1988	16	15.78	27.69	8.99
1989	20	16.20	28.27	9.28
1990	16	16.18	28.25	9.27
1991	12	15.83	27.77	9.03
1992	14	15.69	27.58	8.93
1993	12	15.43	27.21	8.75
1994	9	15.00	26.62	8.45
1995	15	15.00	26.62	8.45
1996	19	15.24	26.95	8.61
1997	17	15.33	27.08	8.68
1998				
1999				
Average	15.33	14.61		

Poisson 0.795168 Poisson 0.845919 cumulative poisson probability
Poisson 0.075151 Poisson 0.064909 probability mass function

Year	Internal Corrosion	Cumulative Average (FE)	UC 95%	LC 95%
1980	5	5.00	11.71	2.14
1981	5	5.00	11.71	2.14
1982	5	5.00	11.71	2.14
1983	7	5.50	12.54	2.41
1984	7	5.80	13.02	2.58
1985	7	6.00	13.35	2.70
1986	9	6.43	14.03	2.94
1987	5	6.25	13.75	2.84
1988	7	6.33	13.88	2.89
1989	10	6.70	14.47	3.10
1990	12	7.18	15.22	3.39
1991	8	7.25	15.33	3.43
1992	9	7.38	15.54	3.51
1993	6	7.29	15.38	3.45
1994	7	7.27	15.35	3.44
1995	11	7.50	15.72	3.58
1996	15	7.94	16.40	3.85
1997	11	8.11	16.66	3.95
1998				
1999				
Average	8.11	6.55		

Poisson 0.999237 Poisson 0.999944 cumulative poisson probability
Poisson 0.001083 Poisson 0.00011 probability mass function


Pipeline Failure rates all causes
Number of Failures
0
5
10
15
20
25
30
35
1980
1985
1990
1995
2000
Year
All pipeline failures
Expected failure rate (cumulative average- all causes)
Upper 95 % Confidence Interval
Lower 95% confidence interval


Pipeline Failure (Internal Corrosion)
Number of Failures
0
2
4
6
8
10
12
14
16
18
1980
1985
1990
1995
2000
Year
internal corrosion Failures
expected failure rate (cumulative average)
upper 95% CI
lower 95% CI

Appendix 7 – Run Details for the Monte Carlo Analyses

Assumptions used for Monte Carlo Calculations

The risk estimate calculation used in the Monte Carlo simulation was

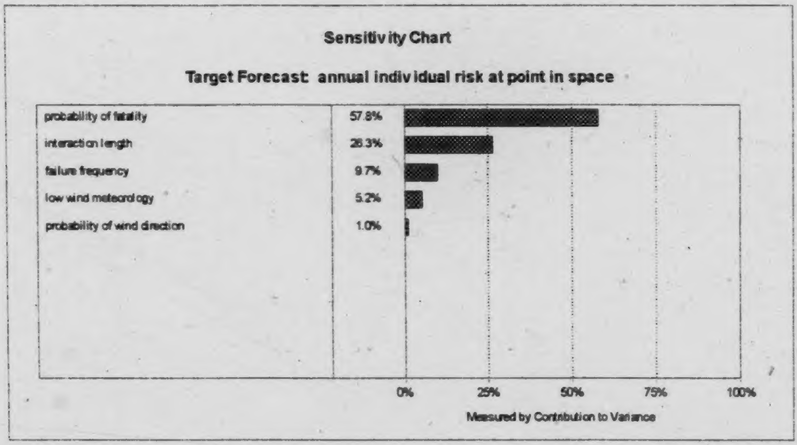
Risk = (interaction length) * (failure frequency) * (probability of non-ignition) *
(probability of release geometry) * (probability of an outdoor receptor) *
(probability of wind direction) * (probability of stable meteorological) *
(probability of fatality) * (probability of exposure)

The distributions used for the variables were

interaction length	triangular
failure frequency	uniform
probability of non-ignition	assumed constant = 1.0
probability of release geometry	assumed to be horizontal = 1.0
probability of an outdoor receptor	assumed constant = 1.0
probability of wind direction	triangular
probability of stable meteorology	triangular
probability of fatality	triangular and uniform (2 separate cases run)
probability of exposure	output distribution generated using Monte Carlo simulation
plume angle	triangular

Crystal Ball Report

Simulation started on 4/16/03 at 13:54:19
Simulation stopped on 4/16/03 at 13:54:32

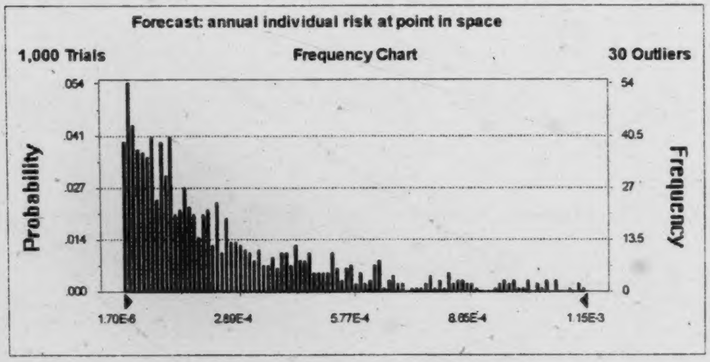


Forecast: annual individual risk at point in space **Cell: D33**

Summary:

Display Range is from 1.70E-6 to 1.15E-3
Entire Range is from 1.68E-7 to 2.78E-3
After 1,000 Trials, the Std. Error of the Mean is 1.01E-5

Statistics:	Value
Trials	1000
Mean	2.82E-04
Median	1.69E-04
Mode	---
Standard Deviation	3.22E-04
Variance	1.04E-07
Skewness	2.47E+00
Kurtosis	1.19E+01
Coeff. of Variability	1.14E+00
Range Minimum	1.68E-07
Range Maximum	2.78E-03
Range Width	2.78E-03
Mean Std. Error	1.02E-05



Forecast: annual individual risk at point in space (cont'd) **Cell: D33**

Percentiles:

Percentile	Value
0%	1.68E-07
10%	2.57E-05
20%	5.53E-05
30%	8.85E-05
40%	1.24E-04
50%	1.69E-04
60%	2.34E-04
70%	3.13E-04
80%	4.44E-04
90%	6.53E-04
100%	2.78E-03

End of Forecast

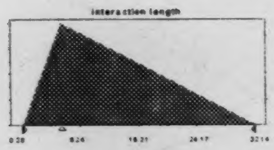
Assumptions

Assumption: interaction length **Cell: D24**

Triangular distribution with parameters:

Minimum	0.28
Likeliest	5.76
Maximum	32.14

Selected range is from 0.28 to 32.14

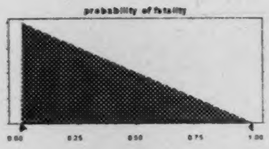


Assumption: probability of fatality **Cell: D25**

Triangular distribution with parameters:

Minimum	0.00
Likeliest	0.01
Maximum	1.00

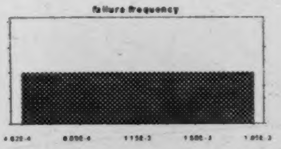
Selected range is from 0.00 to 1.00



Assumption: failure frequency **Cell: D26**

Uniform distribution with parameters:

Minimum	4.62E-04
Maximum	1.85E-03

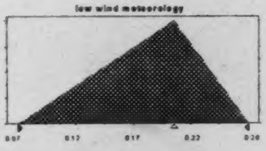


Assumption: low wind meteorology **Cell: D30**

Triangular distribution with parameters:

Minimum	0.07
Likeliest	0.21
Maximum	0.28

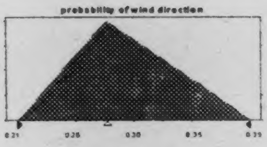
Selected range is from 0.07 to 0.28



Assumption: probability of wind direction **Cell: D29**

Triangular distribution with parameters:

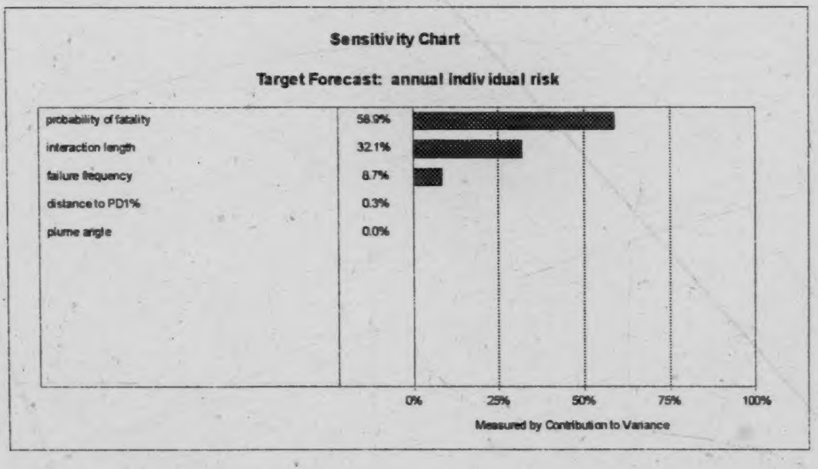
Minimum	0.21
Likeliest	0.28
Maximum	0.39



Selected range is from 0.21 to 0.39

End of Assumptions

Crystal Ball Report
Simulation started on 4/16/03 at 13:42:24
Simulation stopped on 4/16/03 at 13:42:37

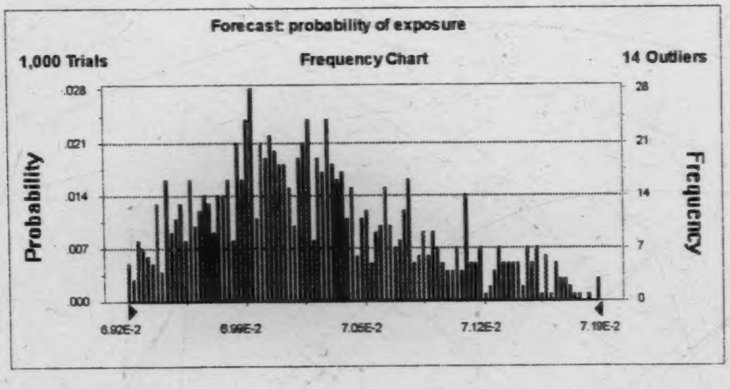


Forecast: probability of exposure **Cell: D31**

Summary:

Display Range is from 6.92E-2 to 7.19E-2
Entire Range is from 6.92E-2 to 7.21E-2
After 1,000 Trials, the Std. Error of the Mean is 2.00E-5

Statistics:	Value
Trials	1000
Mean	7.03E-02
Median	7.02E-02
Mode	---
Standard Deviation	6.33E-04
Variance	4.00E-07
Skewness	6.11E-01
Kurtosis	2.81E+00
Coeff. of Variability	9.00E-03
Range Minimum	6.92E-02
Range Maximum	7.21E-02
Range Width	2.94E-03
Mean Std. Error	2.00E-05



Forecast: probability of exposure (cont'd) **Cell: D31**

Percentiles:

Percentile	Value
0%	6.92E-02
10%	6.95E-02
20%	6.97E-02
30%	6.99E-02
40%	7.00E-02
50%	7.02E-02
60%	7.03E-02
70%	7.05E-02
80%	7.08E-02
90%	7.12E-02
100%	7.21E-02

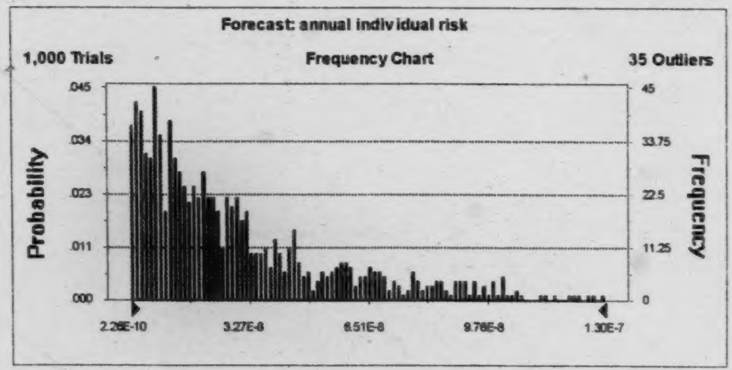
End of Forecast

Forecast: annual individual risk **Cell: D24**

Summary:

Display Range is from 2.26E-10 to 1.30E-7
Entire Range is from 1.84E-10 to 2.70E-7
After 1,000 Trials, the Std. Error of the Mean is 1.15E-9

Statistics:	Value
Trials	1000
Mean	3.33E-08
Median	2.13E-08
Mode	—
Standard Deviation	3.65E-08
Variance	1.33E-15
Skewness	2.28E+00
Kurtosis	9.78E+00
Coeff. of Variability	1.10E+00
Range Minimum	1.84E-10
Range Maximum	2.70E-07
Range Width	2.69E-07
Mean Std. Error	1.16E-09



Forecast: annual individual risk (cont'd) **Cell: D24**

Percentiles:

Percentile	Value
0%	1.84E-10
10%	3.45E-09
20%	7.22E-09
30%	1.14E-08
40%	1.59E-08
50%	2.13E-08
60%	2.82E-08
70%	3.69E-08
80%	5.25E-08
90%	7.91E-08
100%	2.70E-07

End of Forecast

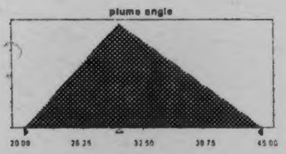
Assumptions

Assumption: plume angle **Cell: D28**

Triangular distribution with parameters:

Minimum	20.00
Likeliest	30.00
Maximum	45.00

Selected range is from 20.00 to 45.00

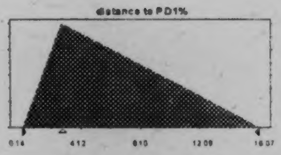


Assumption: distance to PD1% **Cell: D29**

Triangular distribution with parameters:

Minimum	0.14
Likeliest	2.88
Maximum	16.07

Selected range is from 0.14 to 16.07

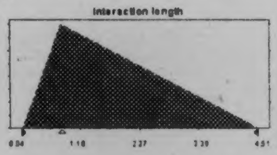


Assumption: Interaction length **Cell: D15**

Triangular distribution with parameters:

Minimum	0.04
Likeliest	0.81
Maximum	4.51

Selected range is from 0.04 to 4.51

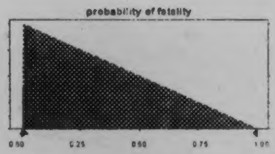


Assumption: probability of fatality **Cell: D16**

Triangular distribution with parameters:

Minimum	0.00
Likeliest	0.01
Maximum	1.00

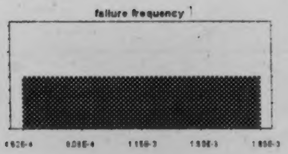
Selected range is from 0.00 to 1.00



Assumption: failure frequency **Cell: D19**

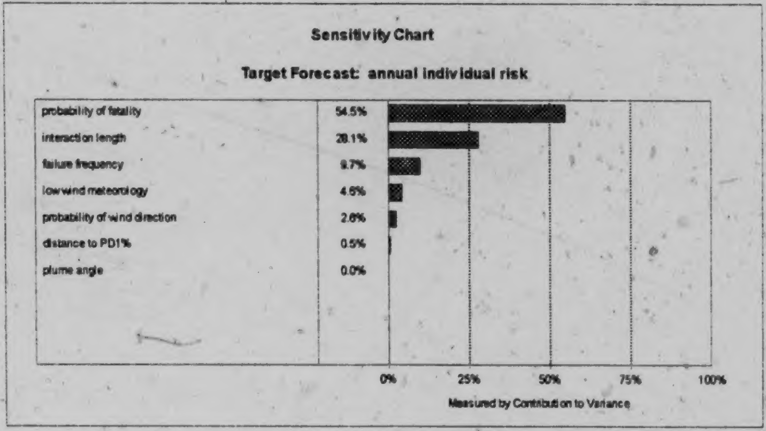
Uniform distribution with parameters:

Minimum	4.62E-04
Maximum	1.85E-03



End of Assumptions

Crystal Ball Report
Simulation started on 4/16/03 at 15:24:36
Simulation stopped on 4/16/03 at 15:24:53



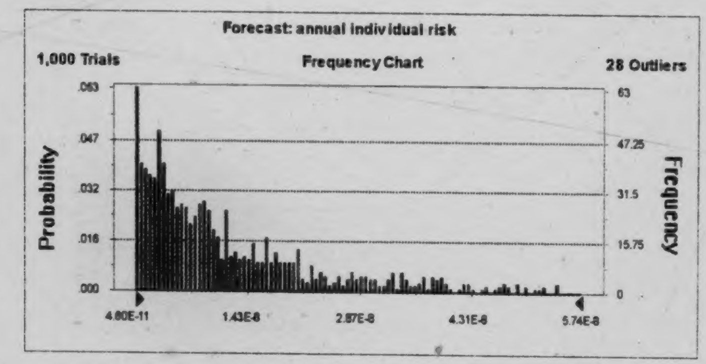
Forecast: annual individual risk **Cell: D35**

Summary:

Display Range is from 4.60E-11 to 5.74E-8
Entire Range is from 1.61E-11 to 1.34E-7
After 1,000 Trials, the Std. Error of the Mean is 5.05E-10

Statistics:

	Value
Trials	1000
Mean	1.36E-08
Median	8.36E-09
Mode	---
Standard Deviation	1.60E-08
Variance	2.55E-16
Skewness	2.63E+00
Kurtosis	1.28E+01
Coeff. of Variability	1.18E+00
Range Minimum	1.61E-11
Range Maximum	1.34E-07
Range Width	1.34E-07
Mean Std. Error	5.05E-10



Forecast: annual individual risk (cont'd) **Cell: D35**

Percentiles:

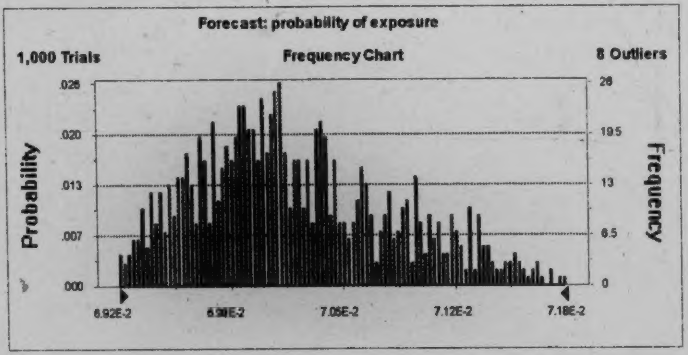
Percentile	Value
0%	1.61E-11
10%	1.14E-09
20%	2.67E-09
30%	4.00E-09
40%	5.99E-09
50%	8.36E-09
60%	1.09E-08
70%	1.54E-08
80%	2.07E-08
90%	3.33E-08
100%	1.34E-07

End of Forecast

Forecast: probability of exposure **Cell: D41**

Summary:
Display Range is from 6.92E-2 to 7.18E-2
Entire Range is from 6.92E-2 to 7.21E-2
After 1,000 Trials, the Std. Error of the Mean is 1.86E-5

Statistics:	Value
Trials	1000
Mean	7.02E-02
Median	7.01E-02
Mode	---
Standard Deviation	5.88E-04
Variance	3.45E-07
Skewness	5.33E-01
Kurtosis	2.68E+00
Coeff. of Variability	8.36E-03
Range Minimum	6.92E-02
Range Maximum	7.21E-02
Range Width	2.94E-03
Mean Std. Error	1.86E-05



Forecast: probability of exposure (cont'd) **Cell: D41**

Percentiles:

Percentile	Value
0%	6.92E-02
10%	6.95E-02
20%	6.97E-02
30%	6.99E-02
40%	7.00E-02
50%	7.01E-02
60%	7.03E-02
70%	7.05E-02
80%	7.08E-02
90%	7.11E-02
100%	7.21E-02

End of Forecast

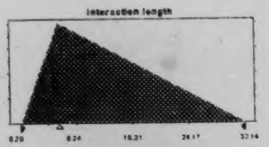
Assumptions

Assumption: interaction length **Cell: D24**

Triangular distribution with parameters:

Minimum	0.28
Likeliest	5.76
Maximum	32.14

Selected range is from 0.28 to 32.14

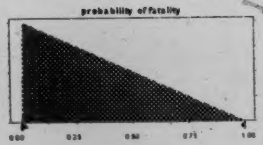


Assumption: probability of fatality **Cell: D25**

Triangular distribution with parameters:

Minimum	0.00
Likeliest	0.01
Maximum	1.00

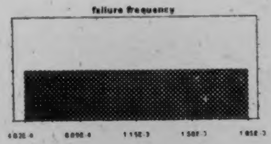
Selected range is from 0.00 to 1.00



Assumption: failure frequency **Cell: D28**

Uniform distribution with parameters:

Minimum	4.62E-04
Maximum	1.85E-03

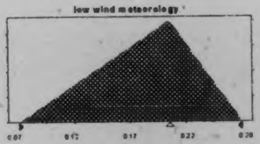


Assumption: low wind meteorology **Cell: D32**

Triangular distribution with parameters:

Minimum	0.07
Likeliest	0.21
Maximum	0.28

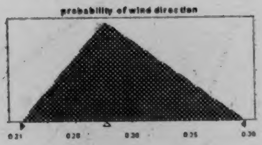
Selected range is from 0.07 to 0.28



Assumption: probability of wind direction **Cell: D31**

Triangular distribution with parameters:

Minimum	0.21
Likeliest	0.28
Maximum	0.39

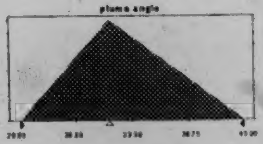


Selected range is from 0.21 to 0.39

Assumption: plume angle **Cell: D38**

Triangular distribution with parameters:

Minimum	20.00
Likeliest	30.00
Maximum	45.00

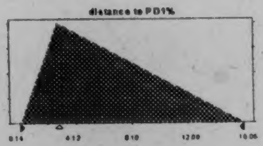


Selected range is from 20.00 to 45.00

Assumption: distance to PD1% **Cell: D39**

Triangular distribution with parameters:

Minimum	0.14
Likeliest	2.88
Maximum	16.06



Selected range is from 0.14 to 16.06

End of Assumptions